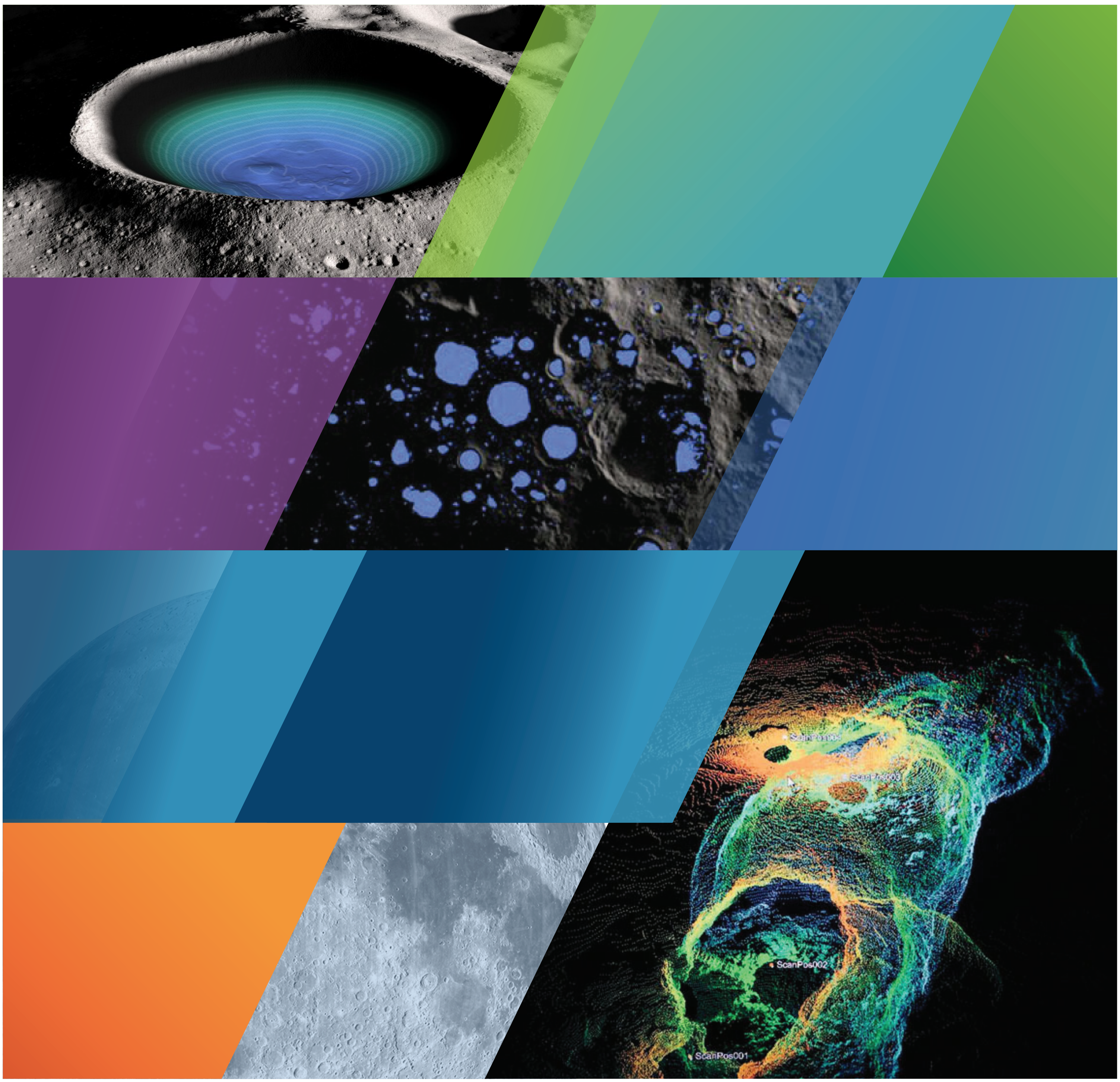
2019
SSERVI ANNUAL REPORT



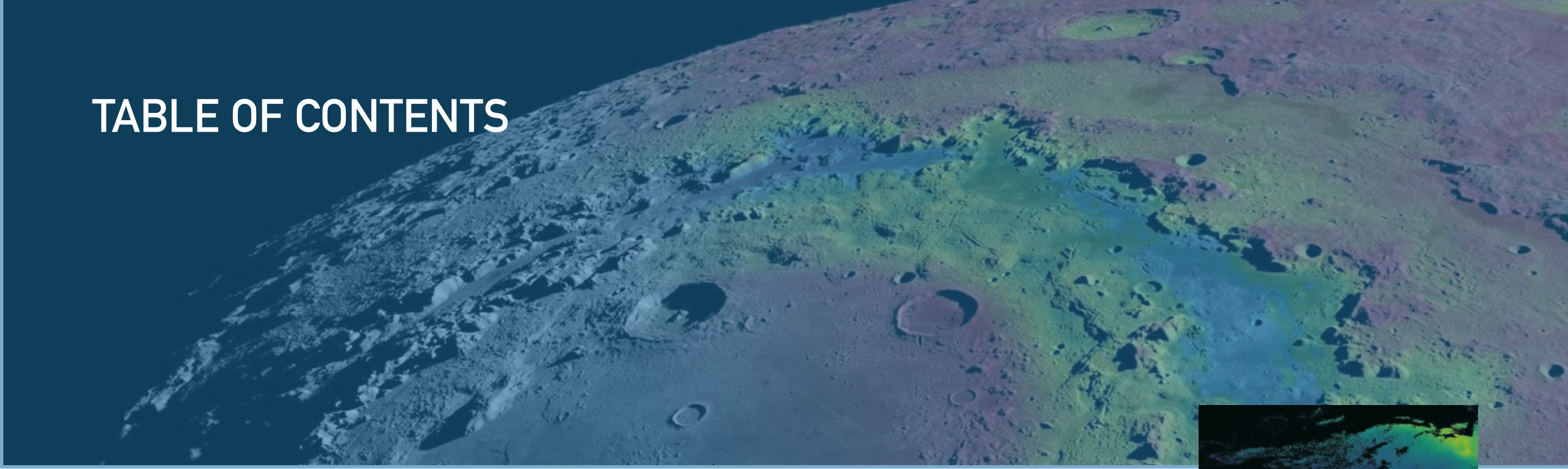
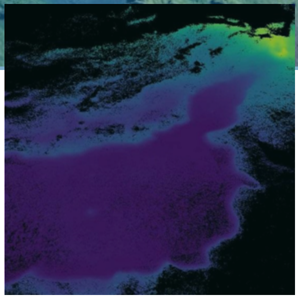
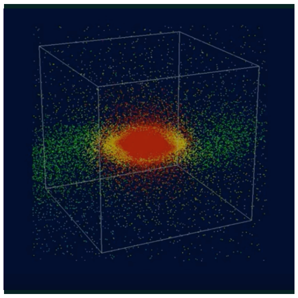
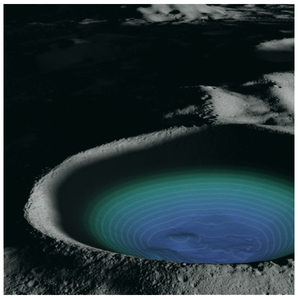
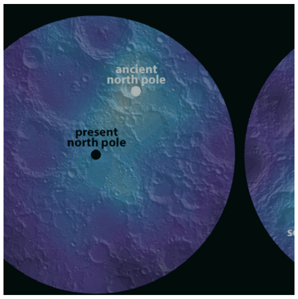


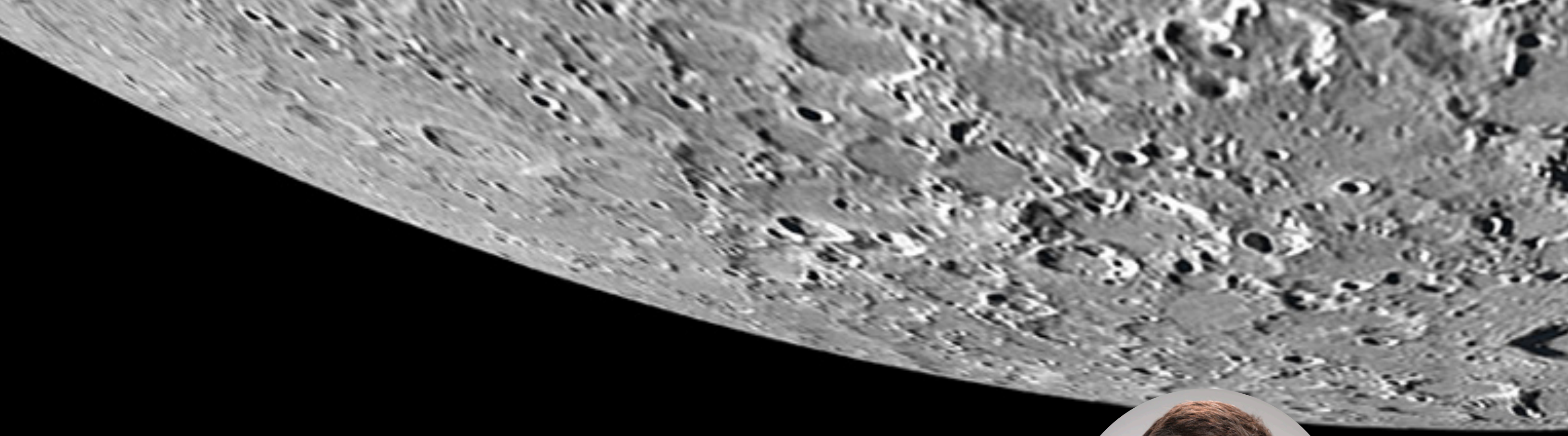
TABLE OF CONTENTS







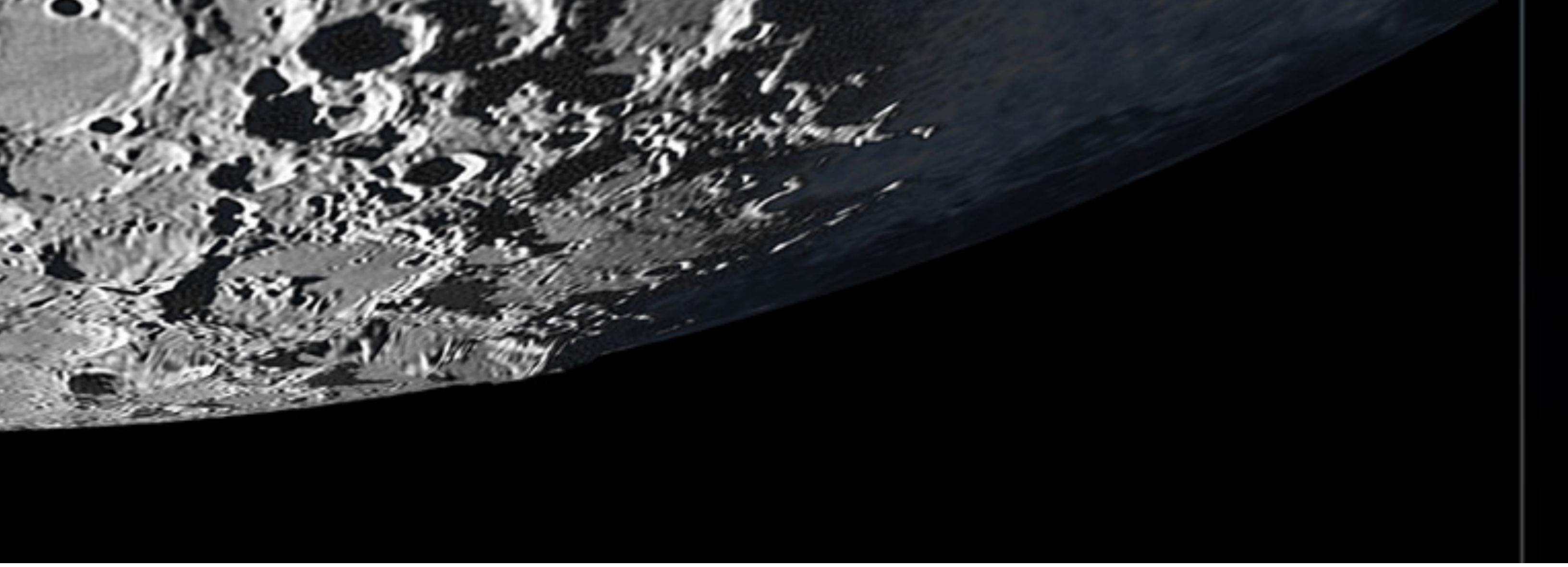




FROM THE BRIDGE

Dear Exploration Science community,

I am very excited to share this 2019 SSERVI Annual Report. You'll notice a lot of new content and new ways of sharing our exciting research results in this report – we hope you benefit as much from it as we have. America has an ambitious future in space exploration. NASA's Artemis program is working to land the first woman and the next man on the Moon by 2024, which in turn will help prepare for a sustainable presence on the Moon and then humanity's next giant leap to Mars. Artemis will push the boundaries of human knowledge like never before, and it's a privilege for SSERVI to be able to help with this important program. SSERVI's teams and international partners are driving exploration science-- the cross-disciplinary science and space exploration research that bridges the human exploration of the solar system with the scientific quest to understand our Sun and planetary neighbors. The premise that exploration enables science and science enables exploration, articulated by the LRO team and popularized by Michael Wargo, captures the heart of SSERVI's mission.The research highlighted in this report continues to reveal new knowledge about the Moon, Earth, and our origins in the solar system. In 2019, NASA selected eight new SSERVI research teams to lead innovative, interdisciplinary research on a wide variety of exploration science topics ranging from geophysics to in-situ resource utilization and many more. We are also eager to see what collaborative discoveries might result from SSERVI's new international partnership with the Japanese Aerospace Exploration Agency (JAXA), signed in July 2019. Their strengths in conducting missions to the Moon, asteroids, and the Martian moons Phobos and Deimos, will be important to NASA as its international partners help carry out the ambitious activities of exploring the Moon with robots and humans. Fifty years ago,



NASA achieved the impossible and landed humans on the Moon. SSERVI, in partnership with its teams and international partners, held Apollo 50th Anniversary events around the world. SSERVI Central organized NASA's only Apollo 11 Splashdown anniversary celebration with a special tribute onboard the U.S.S. Hornet – the historic aircraft carrier that recovered the Apollo 11 crew and capsule from the Pacific after their splashdown on July 24, 1969. Whether as monumental as landing humans on another planetary body for the first time, or as personal as bringing the crew home safely, the event underscored our national determination and resolve to succeed against all odds. In recent months our country has seen major challenges with the unfolding of the coronavirus pandemic and widespread unrest. In spite of these extraordinarily difficult circumstances, I am encouraged to see NASA and our community face these difficult times with courage. Despite the pandemic forcing us apart physically, we are continuing to innovate in virtual science, a core strength of SSERVI. Furthermore, we are standing with those committed to eliminating systemic racism, knowing NASA's mission to benefit humankind can only be done with justice for all. Even with so many obstacles facing us, we aren't paralyzed. We haven't given up. Instead we've worked together to find solutions. And we will continue to press on-- testing the boundaries of what is known, working tirelessly to pioneer the next age of space exploration-- because behind all the technical talent is an unwavering spirit and passion for space. The challenge of doing something new, and what anyone might think is beyond our ability, brings out the very best in humanity. Returning to the Moon will be hard, but by rising to that challenge we can do things that defy imagination and give inspiration for generations to come.

Ad astra,

Gregory K Schmidt

Gregory Schmidt

SSERVI Director

SSERVI.NASA.GOV

twitter.com/NASA_Lunar

facebook.com/NASA.Lunar

Exploration Science enables human exploration or results from it. The guiding principle is that human exploration advances science, and science advances exploration[1].

The Solar System Exploration Research Virtual Institute (SSERVI)

is a virtual Institute at the intersection of science and exploration. It is comprised of a global network of dispersed, interdisciplinary researchers collaborating to address key fundamental science and human exploration questions. The scope of SSERVI research includes NASA's top destinations for human explorers, including NASA's bold plan to go forward to the Moon and beyond through the Artemis Program.

1.This phrase was first developed by Mark Robinson, PI for LROC, and popularized by Mike Wargo, former NASA ESMD Chief Scientist.

PROMOTE

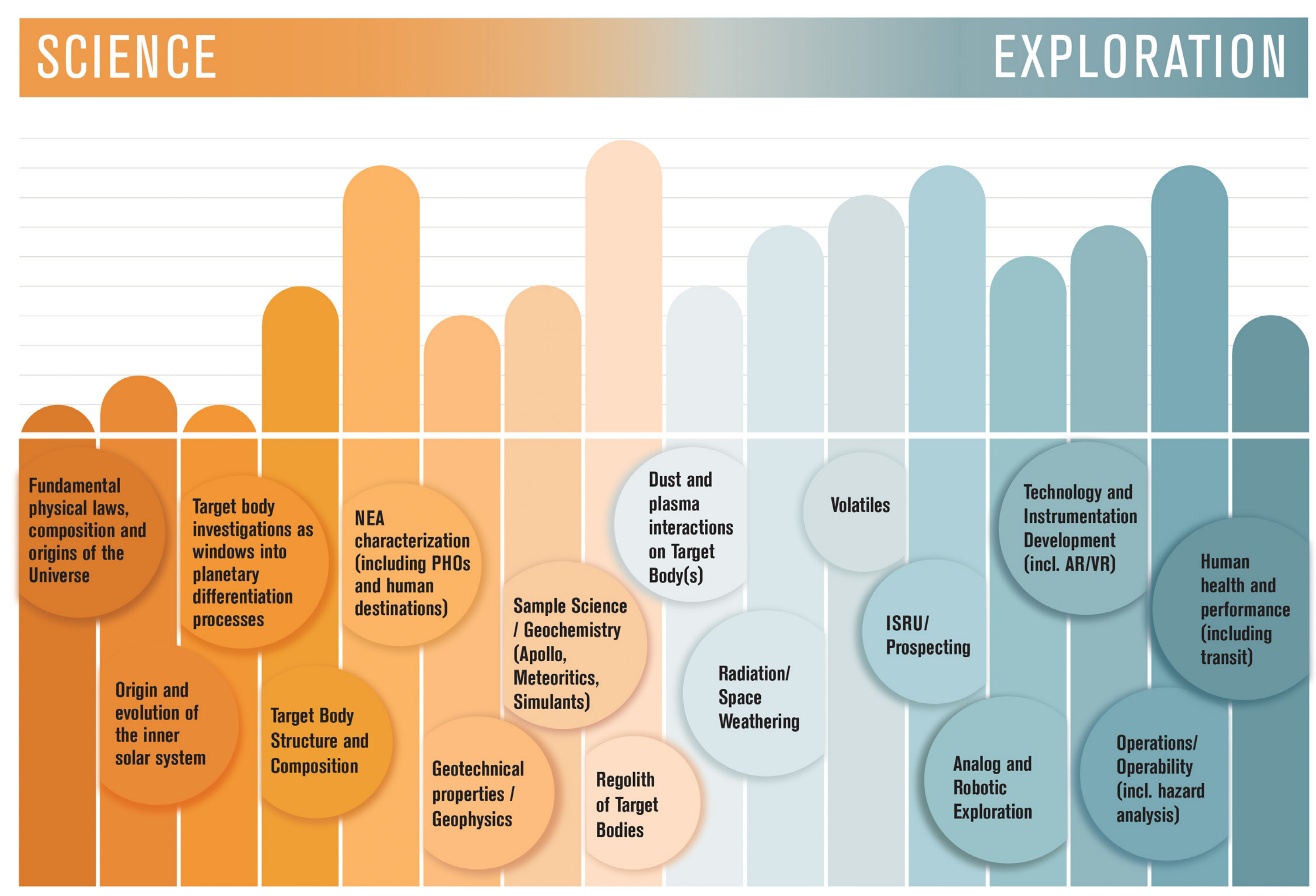
The SSERVI Central Office exercises overall leadership of the institute, setting strategic direction and managing domestic teams in support of science and human exploration. It provides direction and guidance to its teams and international and commercial partners, and promotes the institute's research to NASA HQ and the planetary science and human exploration communities. The research funded by SSERVI addresses complex, multi-faceted questions and each team is funded for 5 years, which allows for flexibility to changing NASA needs as well as allowing research teams to pursue new lines of scientific discovery. Often, this kind of interdisciplinary research would be difficult or not have been achieved in the absence of this funding model. It also provides secure, long-term funding for graduate students and post-doctorate positions. As new questions and results arise, SSERVI can also respond to NASA HQ with expertise within SSERVI to answer NASA's questions pertinent to exploration science and provide critical help to Artemis, VIPER and other agency priorities.

SSERVI has made sustained contributions to the planetary science community and NASA's lunar exploration efforts for well over a decade now (including under its previous name, the NASA Lunar Science Institute). It has led in the advancement of transformative lunar science, and has developed mission, instrument and technology concepts specifically related to exploration science, and has contributed to mission planning and operations through SSERVI's Solar System Treks Portal and innovative AR/VR display systems.

This report includes research summaries from the Cooperative Agreement Notice (CAN)-1 and CAN-2 teams. 261 researchers have been funded through these efforts, with an additional 119 domestic collaborators and 52 international collaborators. As of the end of 2019, SSERVI teams published over 900 peer-reviewed publications, with over 20% having students involved and represented as authors, over 16% as collaborations between teams, and about 14% with international collaboration.

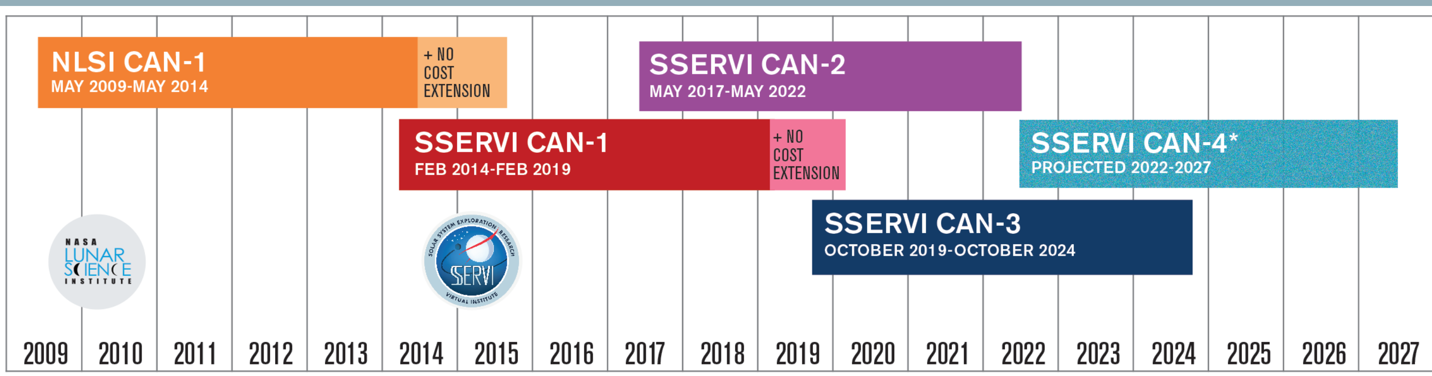
The SSERVI Central Office uses the administrative and technical talents of its staff to effectively bridge SSERVI Teams, International partnerships, and NASA's Science and Human Exploration and Operations Mission Directorates in a wide variety of ways. In 2019, SSERVI leadership, in conjunction with SMD Planetary Science Division and the HEO Advanced Exploration Systems Division leadership selected 8 new teams from the CAN3. The following section highlights selected contributions from the Central Office in support of Institute and Agency mission objectives in 2019.

SSERVI RESEARCH FOCUS



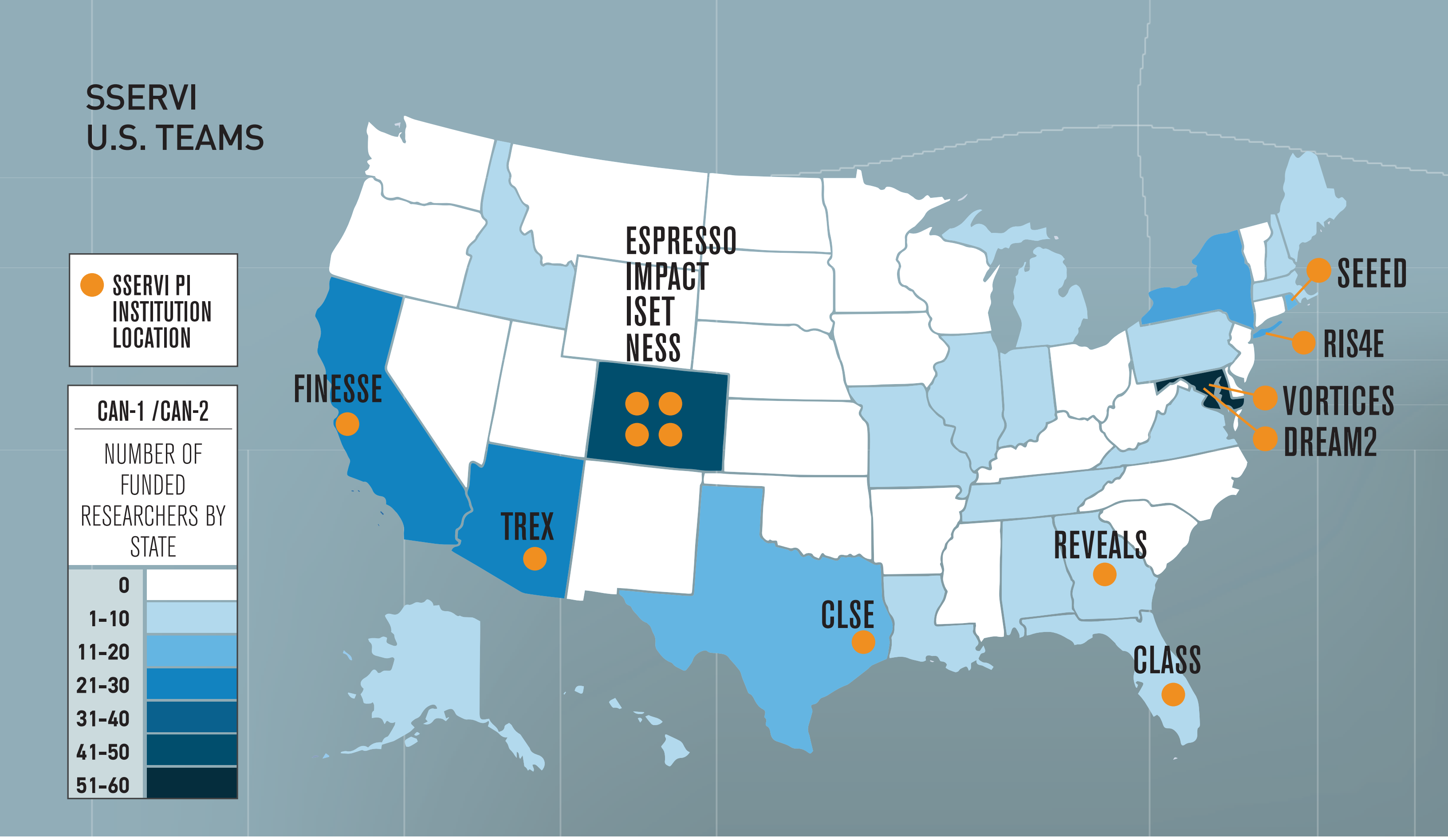
SSERVI research spans the spectrum of fundamental science to human exploration. This chart represents the research focus areas and the bar chart represents the number of SSERVI teams that are addressing a given research area as part of their proposed science.

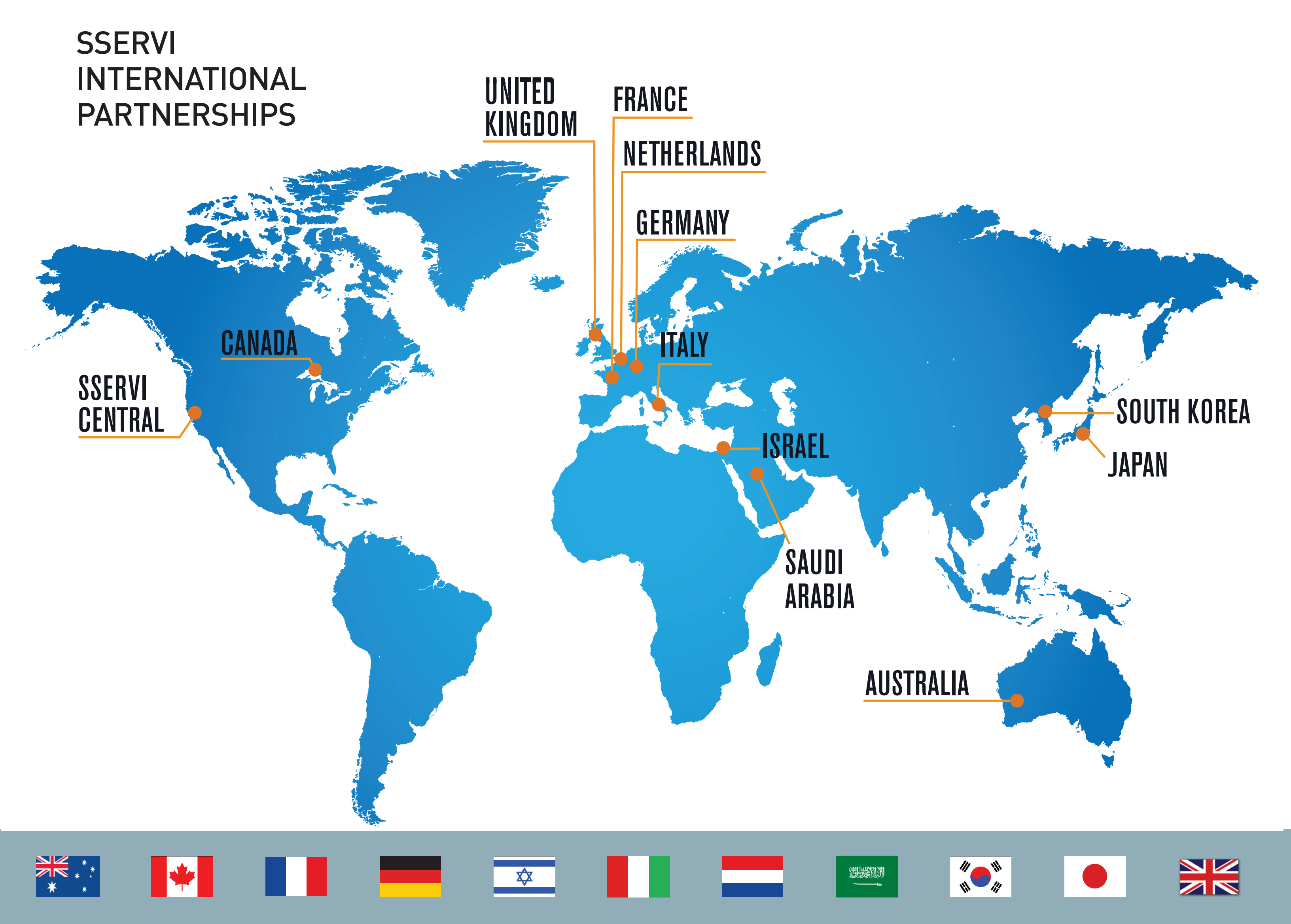
SSERVI Cooperative Agreement Notice (CAN) Roadmap



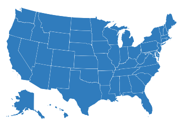
*Tentative schedule for SSERVI CAN 4

Starting with the NASA Lunar Science Institute (NLSI), SSERVI has been awarding 5 year cooperative agreements to selected teams. This graphic represents the historical timing of the previous CANs as well as identifies the timing for the planned SSERVI CAN 4.


SSERVI
U.S. TEAMS
SSERVI PI INSTITUTION LOCATION
CAN-1 /CAN-2
NUMBER OF FUNDED RESEARCHERS BY STATE
0
1-10
11-20
21-30
31-40
41-50
51-60
ESPRESSO
IMPACT
ISET
NESS
FINESSE
TREX
CLSE
REVEALS
CLASS
SEEED
RIS4E
VORTICES
DREAM2


SSERVI
INTERNATIONAL
PARTNERSHIPS
UNITED KINGDOM
FRANCE
NETHERLANDS
GERMANY
ITALY
CANADA
SSERVI CENTRAL
ISRAEL
SAUDI ARABIA
SOUTH KOREA
JAPAN
AUSTRALIA

SSERVI 2019 BY THE NUMBERS



13 Domestic Teams

11 International Partners

CAN 1 + CAN 2 RESEARCHERS

432 Total Individual Team Members* (60 on multiple teams)

261 Individual Domestic Funded Researchers

119 Individual Domestic Collaborators (Unfunded)

52 International Collaborators (Unfunded)

*as proposed

10 PROFESSIONAL TRAVEL AWARDS

14 STUDENT TRAVEL AWARDS

SSERVI PUBLICATIONS 2014-2019

934	SSERVI peer reviewed publications
187	student involved publication (20.3%)
152	cross team collaboration (16.5%)
128	international collaboration (13.9%)

24 VIRTUAL EVENTS

SUPPORTED FOR SSERVI AND COMMUNITY

SSERVI = 19

EC & Site Visit	9
Focus Groups	2
Workshops / Seminars	6
Public Engagement	1
NESF	1

COMMUNITY = 5

SBAG	2
LEAG	1
Centaur Workshop	1
Planetary Defense	1

338 VIRTUAL PRESENTATIONS

SSERVI = 108

EC & Site Visit	25
Focus Group	2
Workshop / Seminars	15
Public Engagement	2
NESF	64

COMMUNITY = 230

SBAG	81
LEAG	29
Centaur Workshop	12
Planetary Defense	108

WEBSITE ANALYTICS

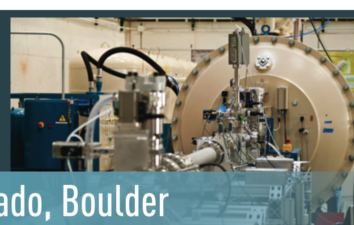
450K Users on Main SSERVI Website

SOCIAL MEDIA ANALYTICS

110K Twitter Followers

SSERVI FACILITIES

Total Number of Facilities= 10



Largest Dust Accelerator at University of Colorado, Boulder

8 TONS of JSC 1A Lunar Regolith Simulant in SSERVI Regolith Testbed

SSERVI SELECTS EIGHT NEW CAN-3 TEAMS

Prof. Daniel Britt
Center for Lunar and Asteroid Surface Science (CLASS)
University of Central Florida, Orlando

Dr. Jeffrey Gillis-Davis
Interdisciplinary Consortium for Evaluating Volatile Origins (ICE FIVE-0)
Washington University in St. Louis, MO

Prof. Timothy Glotch
Remote, In Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2)
Stony Brook University

Dr. Jennifer L. Heldmann
Resource Exploration and Science of OUR Cosmic Environment (RESOURCE)
NASA Ames Research Center

Prof. Mihaly Horanyi
Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT)
University of Colorado, Boulder

Dr. Rosemary Killen
Lunar Environment And Dynamics for Exploration Research (LEADER)
NASA Goddard Space Flight Center

Dr. David A. Kring
Transformative Lunar Science and Exploration
Lunar and Planetary Institute

Dr. Nicholas Schmerr
Geophysical Exploration Of the Dynamics and Evolution of the Solar System (GEODES)
University of Maryland

In 2019 NASA selected eight new research teams at the intersection of spacescience and human space exploration research. NASA's Science (SMD) and Human Exploration and Operations Mission Directorates (HEOMD) will support the new teams for five years. The new teams join four current SSERVI teams to conduct exploration science research in cooperation with U.S and international partners. Sharing data and facilities across teams has hastened scientific discovery, creating cross-disciplinary exchanges and teaming arrangements that otherwise would not have existed. Sharing students, facilities and resources also reduces cost and enhances institute effectiveness. The long-duration funding of teams enables research continuity and the ability to follow new lines of research as discoveries are made. Cooperative agreements allow cooperation between teams and NASA in setting new directions. Furthermore, a series of Cooperative Agreement Notices (CANs) issued every 2.5 to 3 years allows for overlap between generations of Institute teams to provide continuity and continued alignment of the Institute's core research with NASA's changing strategic goals. Per the CAN, NASA may redirect up to 20% of the funding towards focused strategic needs, based on relevant expertise within the teams, to address key human spaceflight concerns.

NASA EXPLORATION SCIENCE FORUM 2019

SSERVI Director Greg Schmidt welcomes attendees to the 2019 NASA Exploration Science Forum.

SSERVI Director, Greg Schmidt, facilitates official signing of the SSERVI / JAXA partnership by Dr. Masaki Fujimoto (Deputy Director General JAXA Institute of Space and Aeronautical Science) and Dr. Lori Glaze (DIrector NASA Planetary Science Division).

The SSERVI Central Office organizes and sponsors the annual NASA Exploration Science Forum (NESF), which brings together several hundred researchers to discuss topics ranging from modeling to mission science. The NESF is a forum where new ideas and innovation are fostered through networking between basic and applied researchers. To date, the NESF is the largest conference dedicated to promoting the intersection of science and exploration. The format of the NESF is flexible with special sessions, talks, panels, exhibitions, and discussions that reflect the direction of the Agency and the community.

The SSERVI Central Office technology team seamlessly integrates virtual presenters and online attendees. The 2019 NESF was attended by 181 people (in-person) and had strong virtual participation (518 live-stream views and 2,106 on-demand views). These virtual metrics were the highest ever recorded for SSERVI, and represent strong global participation by the science and exploration communities. The recorded talks are archived for viewing at: nesf2019.arc.nasa.gov/program.

The 6th annual NESF was July 23-25, 2019 at NASA Ames Research Center, Moffett Field, CA. The 2019 NESF, featured 77 scientific discussions about exploration targets of interest such as the Moon, near-Earth asteroids and the moons of Mars.

Science sessions were focused on recent mission results and in-depth analyses of science and exploration studies. Dedicated side-conferences for graduate students and young professionals and public engagement discussions were interwoven among science topics.

This year's forum included several exciting events, including the Japan Aerospace and Exploration Agency (JAXA) Partnership Agreement signing, and a visit to the U.S.S. Hornet on the 50th anniversary of the Apollo 11 Splashdown. A special talk was given by Apollo 17 astronaut Harrison Schmitt who discussed how Apollo provided insights into key lunar science questions. Other key invited talks included Lori Glaze (NASA Planetary Science Division Updates), Victoria Andrews (U.S. National Near-Earth Object Preparedness Strategy and Action Plan), Jake Bleacher (Artemis Program), Steve Clarke (NASA's Lunar Exploration Campaign: Scientific and Exploration Activities), and John Thornton (Commercial Lunar Payload Services).

This year marked the 50th anniversary of the Apollo 11 mission, and the anniversary of the Apollo 11 splashdown occurred in the middle of the Forum. On July 24, Forum attendees visited the U.S.S. Hornet for a special program. The U.S.S. Hornet–the historic aircraft carrier that recovered the Apollo 11 crew and capsule from the Pacific after their splashdown on July 24, 1969–is now a museum located in the San Francisco Bay with spectacular views of the city, river and sea.

APOLLO 11 SPLASHDOWN
50th Anniversary at U.S.S. Hornet

Apollo 17 astronaut Harrison "Jack" Schmitt visits NASA Ames' exhibit booth. Credit: NASA/SSERVI

Participants had free time to tour the aircraft carrier and exhibits, with docents stationed throughout the exhibits to provide informative educational talks on the U.S.S. Hornet history. In addition, the U.S.S. Hornet Museum partnered with the Aldrin Family Foundation to create an Apollo 50th anniversary wine souvenir. Some of the proceeds from this bottle of 2016 cabernet benefited STEM programs inspiring future generations to "reach for the stars."

"SSERVI is proud to partner with the Aircraft Carrier Hornet Foundation, which preserves and honors the legacy of U.S.S. Hornet, a National and State Historic Landmark, and its role in naval aviation history, the defense of our country, the Apollo Program, and exploration of space," said SSERVI Director Greg Schmidt.

The Splashdown 50th Anniversary event at the U.S.S. Hornet included the following events:

- An Apollo 11 recovery retrospective, where Hornet crew reflected on their personal experiences helping with the Apollo 11 splashdown

- A Science panel discussing lunar geology of the past, present and future, featuring Apollo 17 astronaut Jack Schmitt, who walked on the Moon most recently, as well as planetary scientists David Kring, Jennifer Heldmann and graduate student Ariel Deutsh

- A ceremony was held for Ben Feist from the Apollo 11 Movie to give Michael McCarron, the Executive Director for the U.S.S. Hornet Museum, the complete collection of audio recordings from the U.S.S Hornet during the Apollo 11 mission, including recordings of both ship to shore communications as well as ship to Mission Control, Houston - a total of roughly 1,000 hours of archival recordings

- A NASA leadership discussing NASA's plans to return to the Moon, featuring Dr. Lori Glaze, director of the Planetary Science Division at NASA HQ, Mr. Steve Clarke, Deputy Associate Administrator of the Science Mission Directorate and head of the Lunar Discovery and Exploration Program, and Dr. Jacob Bleacher, Chief Scientist for the Human Exploration and Operations Mission Directorate at NASA HQ

SSERVI's Apollo 50th pop-up banner exhibit. Credit: NASA/SSERVI

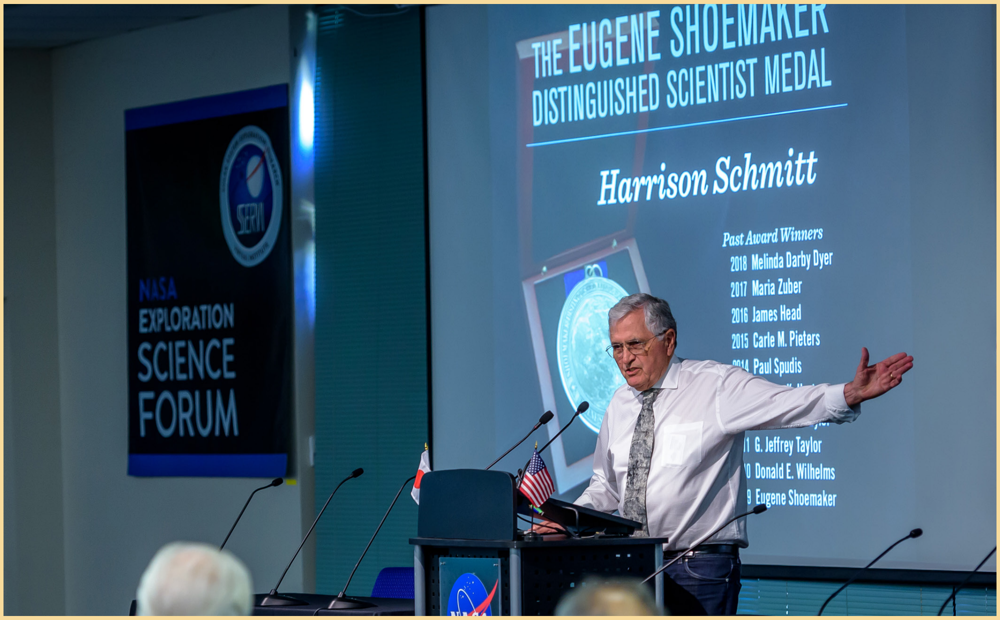
Apollo astronaut Harrison "Jack" Schmitt, inspects SSERVI's touchable Moon rock at the Solar System Treks Portal exhibit. Credit: NASA/SSERVI

NASA EXPLORATION SCIENCE FORUM AWARDS

At the NESF, SSERVI presents awards as a means of honoring key individuals in the community: The Eugene Shoemaker Medal for lifetime scientific achievement, the Michael J. Wargo Award for outstanding achievement in Exploration Science, the Susan Mahan Niebur award for early career achievement, and the Angioletta Coradini Mid-Career Award.

Eugene Shoemaker Distinguished Scientist Medal

The 2019 Eugene Shoemaker Distinguished Scientist Medal, named after American geologist and one of the founders of planetary science, Eugene Shoemaker (1928-1997), is awarded to the honorable Harrison Hagan Schmitt for his significant scientific contributions throughout the course of his career. The award includes a certificate and medal with the Shakespearian quote “And he will make the face of heaven so fine, that all the world will be in love with night.”

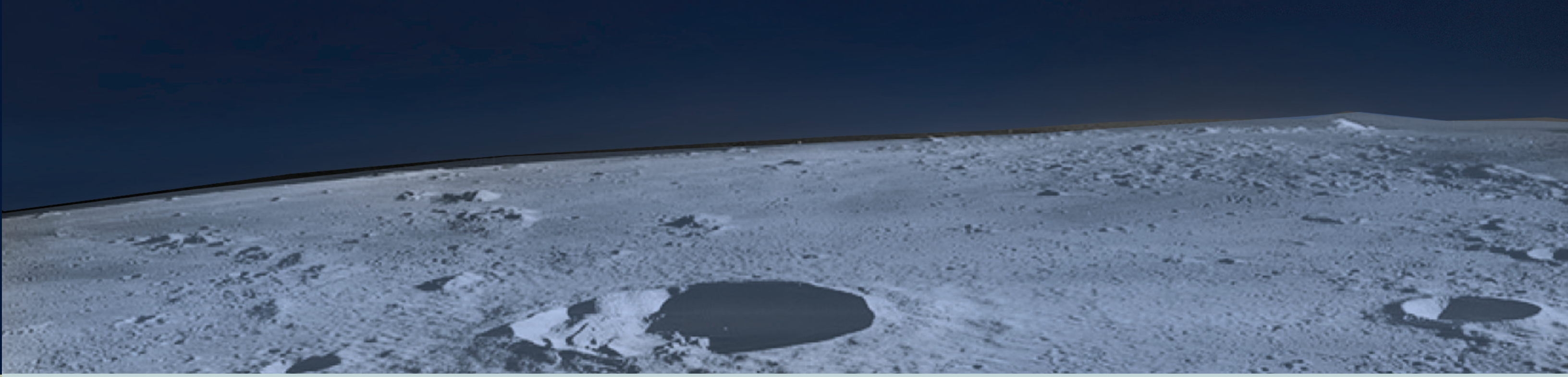


The honorable Harrison Schmitt gives his acceptance speech at the NESF 2019 award presentation.

AWARD NOMINATIONS

The SSERVI awards are open to the entire research community and are presented with invited talks at the NESF. Nominations are welcome at any time but must be submitted in early March for consideration in that calendar year. Recipients need not reside in the U.S. nor be a U.S. citizen. Winners are formally presented with the awards at the NESF each summer. More information on these awards and all recipients can be found at: http://sservi.nasa.gov/awards

Dr. Harrison Hagan Schmitt is an American geologist, retired NASA astronaut, university professor, and former U.S. senator from New Mexico. Schmitt received his Ph.D. in geology from Harvard University in 1964, and was selected as one of the first group of scientist-astronauts in 1965. He played a key role in training Apollo crews to be geologic observers both in lunar orbit and on the surface, and participated after each landed mission in examination and evaluation of the returned samples. As one of the Apollo 17 crew, Schmitt is the most recent living person to have walked on the Moon, and was the photographer who took the famed “Blue Marble” shot of Earth. Schmitt also remains the first and only professional scientist to have flown beyond low Earth orbit and to have visited the Moon. Schmitt resigned from NASA in August 1975 in order to serve in the United States Senate, and served as the ranking member of the Science, Technology and Space Subcommittee. He has since served as chair of the NASA Advisory Committee in addition to his many other roles, wrote a book entitled Return to the Moon: Exploration, Enterprise and Energy in the Human Settlement of Space in 2006, and has maintained an active scientific career, particularly with his focus on helping a new generation of lunar scientists.



Michael J. Wargo Exploration Science Award

The Michael J. Wargo Exploration Science Award is an annual award given to a scientist or engineer who has significantly contributed to the integration of exploration and planetary science throughout their career. Dr. Michael Wargo (1951-2013) was Chief Exploration Scientist for NASA's Human Exploration and Operations Mission Directorate and was a strong advocate for the integration of science, engineering and technology. The 2019 Michael J. Wargo Exploration Science Award is given to Dr. Wendell Mendell who retired in 2013 after working over 50 years at the Johnson Space Center as a NASA planetary scientist.

Dr. Wendell Mendell at the NESF 2019 award presentation.

Dr. Wendell Mendell served as Assistant Administrator for Exploration in the Directorate for Astromaterials Research & Exploration Science of the NASA Johnson Space Center, and in the Constellation Systems Program Office as Chief, Office for Lunar & Planetary Exploration where he acted as a liaison between the scientific community and the Program responsible for implementing the Vision for Space Exploration. He has long advocated for human exploration of the solar system, and for the establishment of a permanent human base on the Moon. His interests lay as much with policy issues as with technical solutions. Dr. Mendell has a B.S. in physics from CalTech; a M.S. in physics from UCLA; and a M.S. in Space Science and a Ph.D. in Space Physics and Astronomy from Rice University. His scientific research focus was on remote sensing of planetary surfaces, particularly specializing in thermal emission radiometry and spectroscopy of the Moon. He has published over 40 articles in professional journals and conference proceedings and authored numerous abstracts and short papers presented at technical conferences.

SSERVI Director Greg Schmidt and former SSERVI Deputy Director Brad Bailey pose with the 2019 NESF Award winners.

Dr. Jennifer Heldman offers some inspiring words at the NESF 2019 award presentation.

Angioletta Coradini Mid-Career Award

The SSERVI Angioletta Coradini Mid-Career Award is given annually to a mid-career scientist for broad, lasting accomplishments related to SSERVI fields of interest. Angioletta Coradini (1946-2011) was an Italian planetary scientist who has inspired astronomers around the world. The 2019 Angioletta Coradini Mid-Career Award is given to Dr. Jennifer Heldmann at NASA Ames Research Center.

Dr. Heldmann received her B.S. in Astrogeophysics from Colgate University, a M.S. in Space Studies, with a Minor in Geology, from University of North Dakota, and her Ph.D. in Planetary Science from the Univ. of Colorado at Boulder. Her scientific research is focused on studies of the Moon and Mars. She is involved in planning for the future human exploration of Mars and has served on several Mars Exploration Program Analysis Group special action teams for defining precursor activities needed to enable future human exploration of Mars. She has also served as the NASA Science Mission Directorate (SMD) Lead for the “Optimizing Science and Exploration Working Group” to connect SMD science objectives with NASA’s human exploration plans for the inner Solar System. In addition to these planning activities, Heldmann actively participates in research and field campaigns to enable human and robotic exploration of the Solar System. She was on the Science Team, Payload Team, and was the Observation Campaign Coordinator for NASA’s Lunar Crater Observation and Sensing Satellite (LCROSS) mission to study the permanently shadowed regions of the lunar poles. She is the Principal Investigator (PI) for SSERVI’s FINESSE (Field Investigations to Enable Solar System Science & Exploration) team, and is PI and Co-I on numerous other NASA projects and grants.

Dr. Debra Needham gives some advice to early career researchers at the NESF 2019 award presentation.

Susan Mahan Niebur Early Career Award

The 2019 Susan Mahan Niebur Early Career Award is an annual award given to an early career scientist who has made significant contributions to the science or exploration communities. Recipients of the Susan M. Niebur Early Career Award are researchers who are no more than ten years from receiving their PhD, who have shown excellence in their field and demonstrated meaningful contributions to the science or exploration communities. Susan Mahan Niebur (1978-2012) was a former Discovery Program Scientist at NASA who initiated the first ever Early Career Fellowship and the annual Early Career Workshop to help new planetary scientists break into the field. This year the prize is presented to Dr. Debra Needham, planetary scientist at NASA’s Marshall Space Flight Center in Huntsville, Alabama.

Dr. Needham has investigated surface processes such as volcanic eruptions and lava flow emplacement on the Moon, Mars, Venus, and Earth. She also works with several teams of engineers to integrate science into developing exploration opportunities such as the Deep Space Gateway and lunar surface missions. She earned her BA in Geology from Pomona College in 2007, her MS in Geosciences from Brown University in 2009, and her PhD in Geosciences from Brown University in 2012. Dr. Needham joined the Heliophysics and Planetary Science Group (ST-13) at Marshall Space Flight Center in 2016, where she continues her research of volcanic eruptions on Earth, the Moon, Mars, and Venus. This work is leading to new exciting investigations and discoveries that will influence future missions to the lunar surface.

Focus Groups

SSERVI's Focus Groups are open to the entire community. Each addresses a topical area of particular community interest and are a way of sharing and coordinating research objectives in the broad community. Focus Groups provide venues for developing research areas across the broad exploration science community, stimulating new areas of research, promoting long-distance collaborations, and contributing to space mission concepts and instrumentation. SSERVI supports Focus Groups in several ways, including hosting online meetings, workshops, field trips, and/or other activities that support the Group's objectives. Since 2009, SSERVI has coordinated and supported 9 focus groups, yielding a multitude of white papers as well as specific studies and reports that have been helpful in informing NASA on key strategic objectives and establishing new directions. During the 2019 NESF, four focus groups met in person to further discuss their specific topics.

Student Poster Competition and Lightning Round Talks

SSERVI has held the annual student poster competition at the NESF since 2009 to provide motivation, encouragement, and recognition to young researchers. Students competing for the awards are encouraged to give a one-minute lightning talk during special sessions at the NESF to briefly summarize their research and poster. Their presentations and posters are evaluated by a committee of senior researchers, and award winners receive a $1000 travel grant to a scientific meeting of their choice. Selection criteria include the originality of the research, quality and clarity of the presentation (including accessibility to the non-expert), and impact to science and exploration.

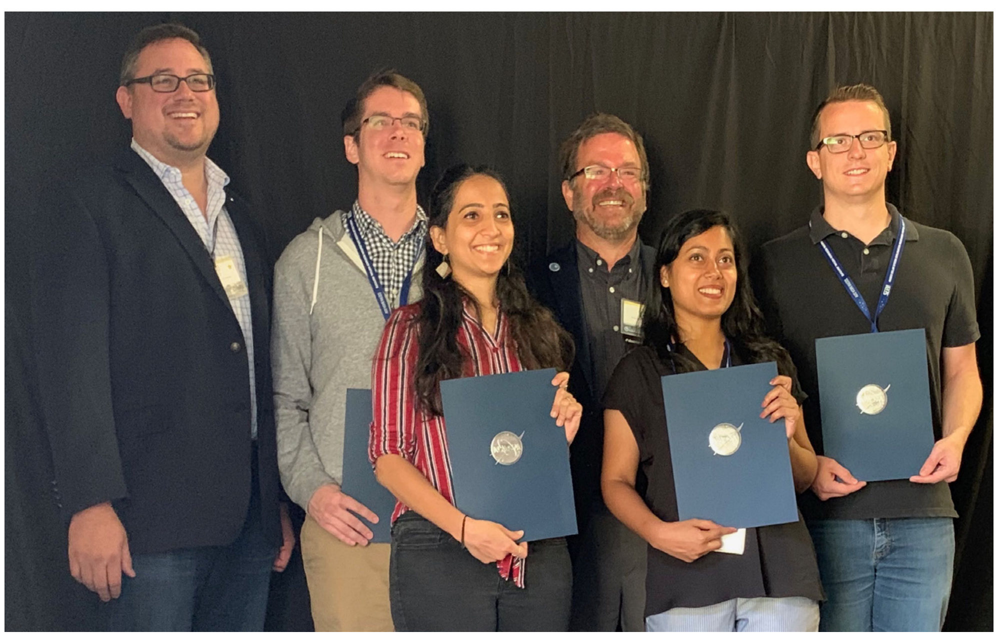
2019 NASA Exploration Science Forum Student Poster Competition winners:

First place was awarded to **Nevadida Mahesh** for the poster *"Modelling planar dipoles on lunar regolith for a radio array on the lunar farside."*

Second place was awarded to **William Goode** for the poster *"Chemical composition of particles from Europa's surface."*

Third place was awarded to **Virginia Daar** for the poster *"Composition dependent simulated space weathering effects on hydroxyl interactions on silicon films."*

Honorable mention was awarded to **Leslie Chambers** for the poster *"Grit: a plume surface interaction experiment in vacuum microgravity."*



SSERVI Director Greg Schmidt and former SSERVI Deputy Director Brad Bailey pose with the 2019 Student Poster Award winners.

Lunar Grad Conference

The 9th annual Lunar and Small Bodies Graduate Conference, LunGradCon, is held each year adjacent to the NESF and provides opportunities for networking with fellow grad students and postdocs, as well as senior members of SSERVI. The conference is held one day before the NASA Exploration Science Forum (NESF), is run by and for graduate students studying the Moon and other airless bodies. Because the conference is composed only of graduate students, undergrads, and postdocs, it provides an excellent opportunity for students to practice presenting their research to a technical audience in a low-stress environment.

This year featured 25 talks and attendees from 21 different institutions over subjects ranging from potential hazards for human-crewed missions to the topography of Ultima Thule. Chaired sessions were focused on exploration science, space physics, dust, moons, and small bodies. These topics overlap with those that are investigated by SSERVI, allowing students to attend the NESF immediately following LunGradCon to further present to, learn from, and network with the broader exploration science community.

2019 LunGradCon Group Photo

More information and abstracts from the 2019 LunGradCon can be found at:

http://impact.colorado.edu/lungradcon/2019/

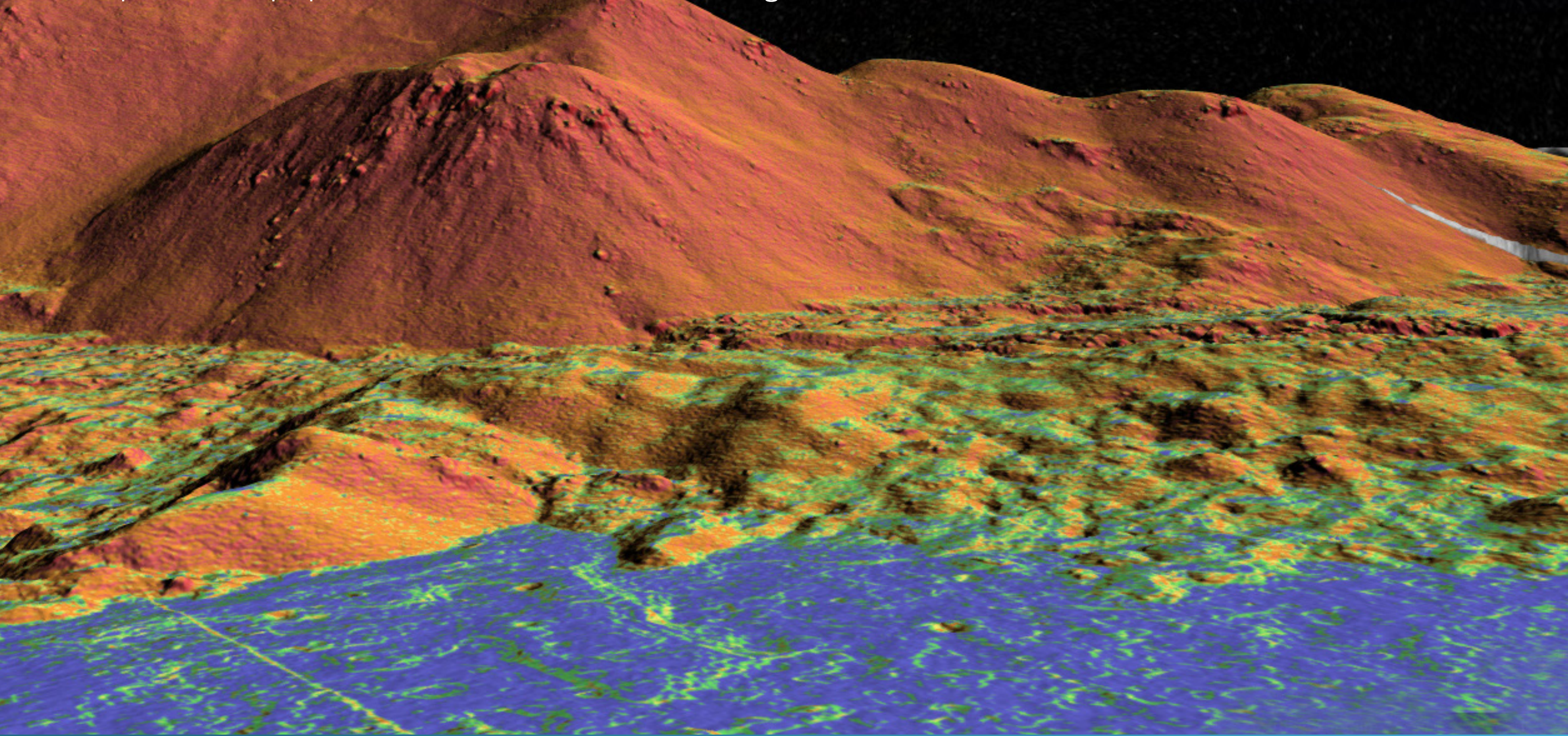
Students interested in attending LunGradCon 2020 are encouraged to send an email to lungradcon@gmail.com to receive registration information when it becomes available. Limited travel and hotel funds are available.

Local Artist Honors Apollo 11

Kayla Jimenez was born at 26 weeks and, weighing only one pound, she was not expected to survive-- but she did! Due to her premature birth, Kayla has permanent disabilities, including cerebral palsy, epilepsy, autism, learning disabilities, and early stage glaucoma and lattice degeneration in both eyes. But Kayla's love for art came at a very early age and she blossomed into a self-taught professional watercolor artist. Kayla was honored to have her Splashdown painting recognized for the 50th Anniversary of Apollo 11, and SSERVI was pleased to showcase her painting at the NESF in celebration of this historic moment in history.

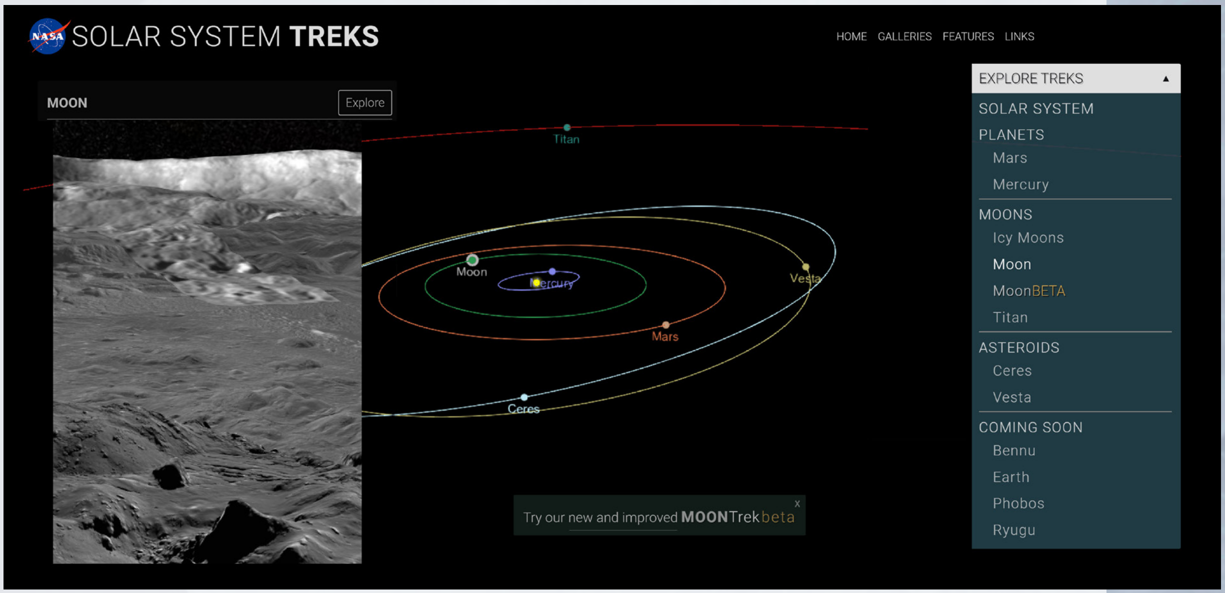
SOLAR SYSTEM TREKS PROJECT

NASA's Solar System Treks (SSTP) is a SSERVI project managed through the institute's Central Office, and developed and operated by the project's team at JPL. The web-based Portals and interactive visualization and analysis tools enable mission planners, lunar and planetary scientists, engineers, students, and the public to access data products from many lunar and planetary missions. During the past year, the Trek suite expanded to include additional planetary bodies, and has been tasked with providing detailed visualization and analysis capabilities for proposed future human and robotic landing sites on the Moon and Mars.

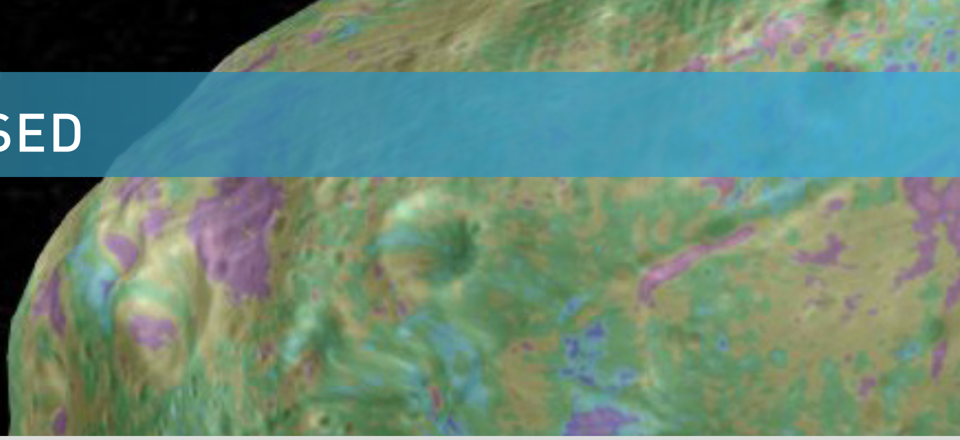


SOLAR SYSTEM TREKS HOME SITE

With the growth in the number of portals, a unifying site **(https://trek.nasa.gov)** now provides easy access to all of the portals along with supporting content including tutorial videos, libraries of video and virtual reality tours, and Planetary Feature of the Month articles.

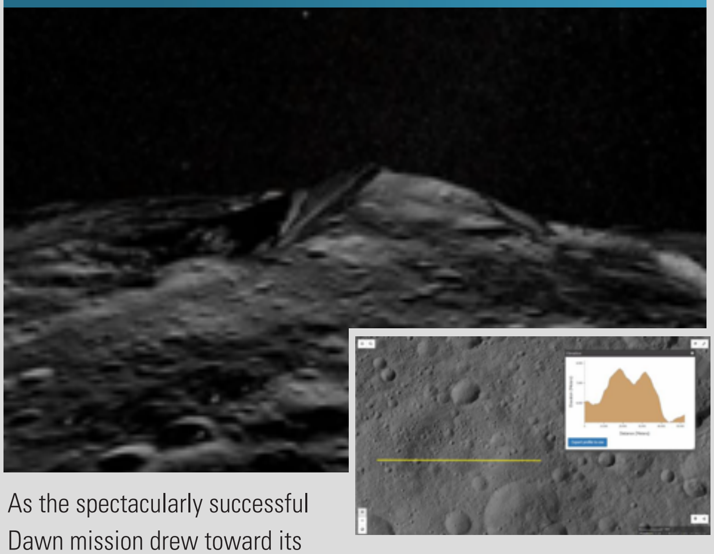


NEW PORTALS RELEASED



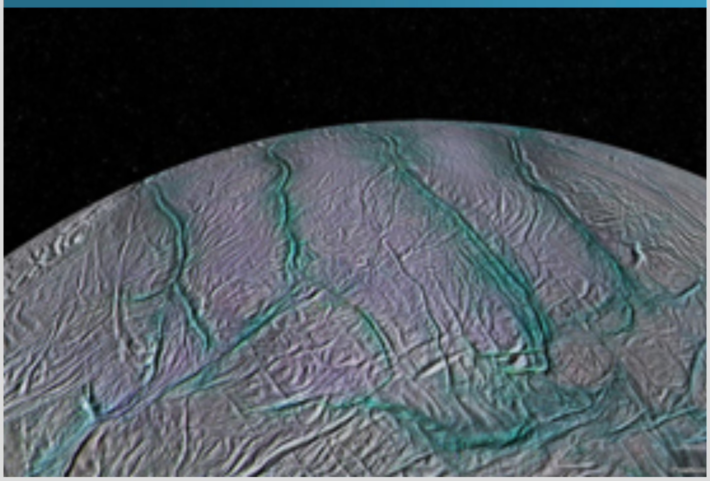
During the course of 2019, SSTP released four new portals and launched a new home site providing integrated access along with supporting content.

CERES TREK



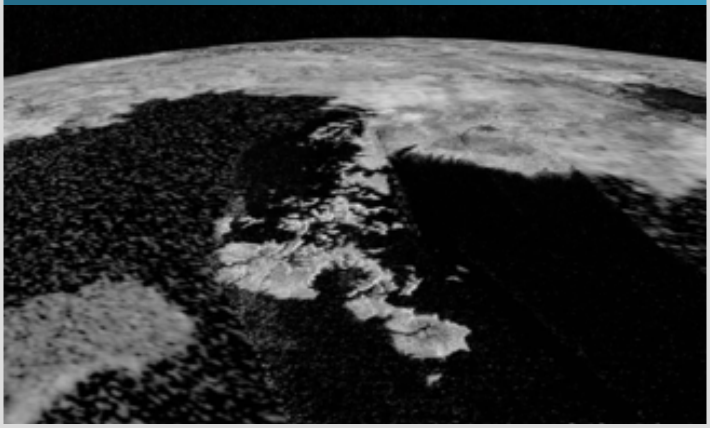
As the spectacularly successful Dawn mission drew toward its conclusion, mission management commissioned SSTP to create a portal featuring its data gathered while in orbit around Ceres.

ICY MOONS TREK



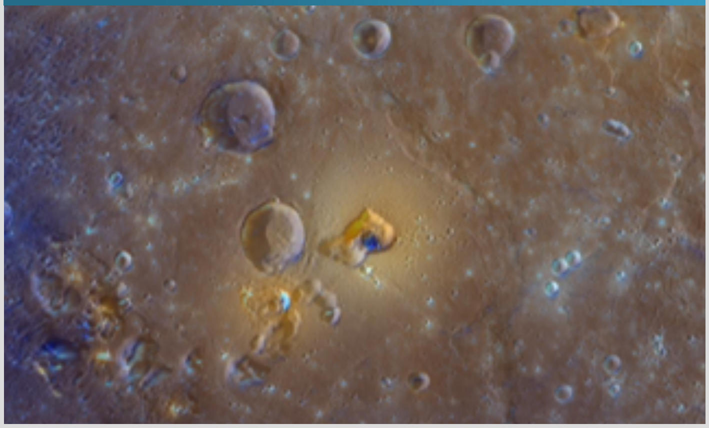
A unifying portal, Icy Moons Trek, was developed for Cassini data from seven of Saturn's smaller, icy moons: Dione, Enceladus, Iapetus, Mimas, Phoebe, Rhea, and Tethys.

TITAN TREK



With the completion of NASA's Cassini Mission's exploration of Saturn and its Moons, SSTP to created two new portals to visualize this data. The first of these portals to be made public was Titan Trek, which features a powerful new catalog and enhanced search capabilities that will become standard across the Trek portals.

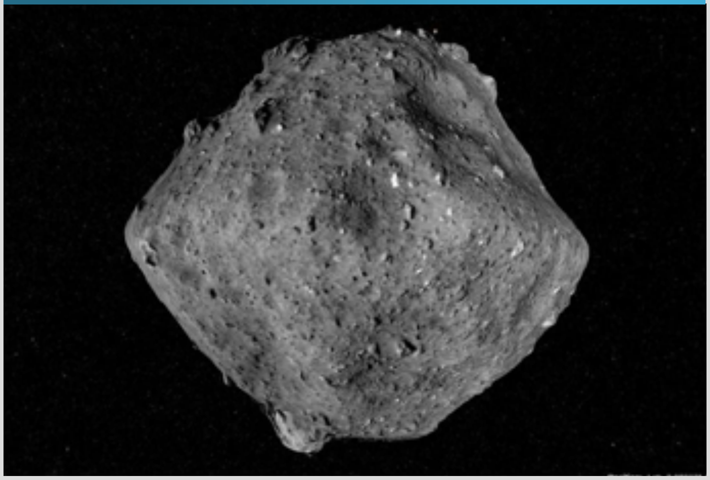
MERCURY TREK



Go Murakami of JAXA, requested a portal featuring MESSENGER data from Mercury that could be used to for mission planning and visualization of the BepiColombo Mission.

NEW PORTALS UNDER CONSTRUCTION

RYUGU TREK PROTOTYPE

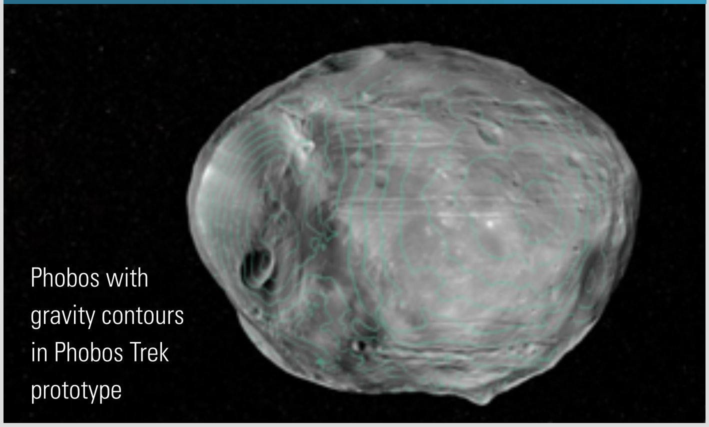


At the request of NASA and JAXA management, SSTP produced a prototype portal for the near-Earth asteroid Ryugu, in support of the Hayabusa2 mission. The team continues work with JAXA to ingest new, high-resolution data from Hayabusa2.

BENNU TREK PROTOTYPE

At the request of the OSIRIS-REx Mission, we produced a prototype portal for the near-Earth asteroid Bennu. The team is continuing work with OSIRIS-REx to ingest new, high-resolution data and maximize the portal's utility for the mission.

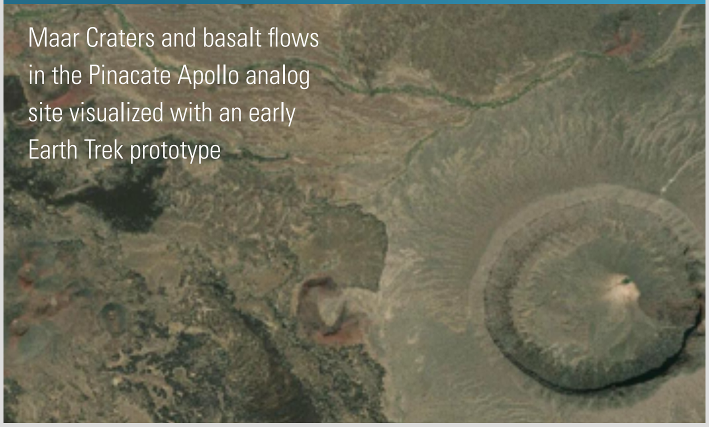
PHOBOS TREK PROTOTYPE



Phobos with gravity contours in Phobos Trek prototype

Continuing collaboration with JAXA and ESA in support of their upcoming MMX Mission, SSTP is developing a portal for Mars' moon Phobos.

EARTH TREK PROTOTYPE

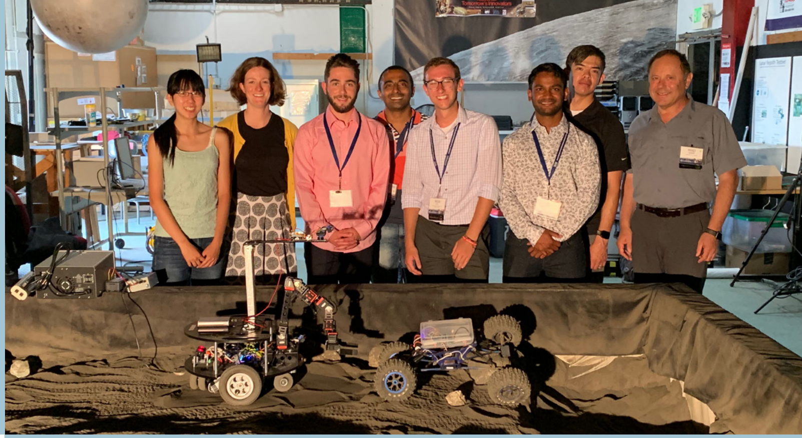


Maar Craters and basalt flows in the Pinacate Apollo analog site visualized with an early Earth Trek prototype

SSTP is developing an Earth Trek portal for Moon and Mars analog sites here on Earth. Discussions with SSERVI's Australian partner raised the fascinating possibility of an Earth portal being used to study meteoritics and past Earth impacts in support of NASA planetary defense efforts.

LUNAR LAB REGOLITH TESTBED

SSERVI manages the lunar lab regolith testbed at NASA Ames which contains eight tons of JSC-1A lunar regolith simulant. The facility is available to SSERVI teams as well as other NASA researchers and partners.



In collaboration with the SHARP Lab, members from three SSERVI teams (CLASS [Britt], IMPACT [Horanyi], NESS [Burns] conducted research simultaneously in the Lunar Lab/Regolith testbed.

SSERVI supported the following four major activities in the testbed in 2019. In May, Rick Elphic, in partnership with Honeybee Robotics, used a custom-built rig in the lunar lab to demonstrate a spectrometer's ability to penetrate through layers of regolith to detect water at various depths. The integrated instrument has the capability to directly assess the composition of subsurface materials using an instrumented planetary drill. This instrument can significantly enhance future missions by providing a means to "measure while drilling." This capability supports robotic and autonomous exploration of the Moon, Mars and small bodies throughout the solar system. Its applicability extends to both science and exploration ISRU missions for decision support in both robotic and human surface exploration scenarios.

Ames Intelligent Robotic Division used a custom-built rig to simulate Mars gravity conditions and test wheel operation in the regolith testbed.

In an excellent example of cross-team collaboration, members from three SSERVI teams conducted research simultaneously in the facility. Jack Burns' (NESS) students tested a teleoperated rover arm as a human-robotic construction system in the testbed. Mihaly Hornayi's (IMPACT) student, Yeo Li Hsia, investigated lunar and asteroid dust electrically charged by moving rover wheels. Addie Dove (CLASS) provided expertise and historical information for the experiment that she initiated years ago, and co-authored the project to completion. These tests coincided with the joint SSERVI and Systems Health, Analytics, Resilience, and Physics-modeling (SHARP) Lab Uplink Rover research project. George Goropse provided technical support for the Uplink Rover experiment, and provided test equipment and expertise between all the projects that proved to be quite valuable to everyone.

Uland Wong (right) hosted the VIPER pre-PDR review team that toured the facility.

Arno Rogg of the Ames Intelligent Robotic Division used the lab to develop a single-wheel testing rig for Lunar and Mars rover wheel designs. With the ability to simulate various terrain, surface conditions and low gravity, the versatile test rig will be useful for testing future wheel designs.

Uland Wong, also from Ames Intelligent Robotic Division, used the facility for follow-on research with stereo lighting experiments. The results of his work are being used by NASA's VIPER mission to better understand how different lighting conditions may affect resource prospecting.

INSPIRE

Engaging the public in the excitement of NASA's mission is a critical part of SSERVI's charter. SSERVI's Public Engagement efforts are centered around inspiring the next generation to learn about our science, and informing the public of what NASA and its partners are planning for future human exploration of the Moon and beyond. Public Engagement is accomplished at SSERVI both through its Central office and the SSERVI teams, which are funded to enable the science activation/citizen science/public engagement ecosystem that NASA has created. Teams are expected through these efforts to implement activities furthering some aspect(s) of Science, Technology, Engineering, Art, and Math (STEAM) engagement. A summary of each team's public engagement efforts is included in their respective team reports.

SSERVI Central is involved in a wide variety of activities including: making public lectures and providing and staffing exhibits at many events— scientific, educational and public; visiting schools to do activities with students, teachers, and under-served communities, and training teachers in key activities; and working with citizen scientists to provide input to various programs such as the Global Fireball Network. The following section highlights selected contributions from the Central Office in support of inspiring the public in 2019.

NASA NIGHT WITH THE SAN FRANCISCO 49ERS

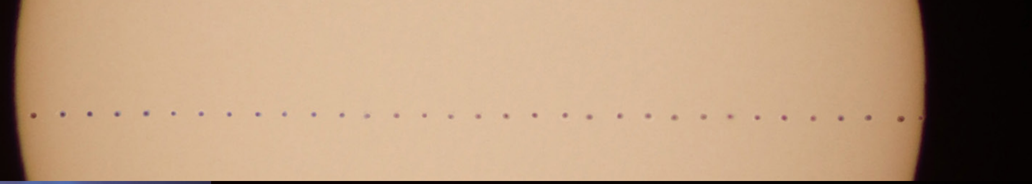
The event received special recognition from the NFL and even made the NFL's "Best Practices" newsletter – which is big news!

With ~70k people in attendance, this was an exciting event to say the least! NASA had a great time interacting with 49er fans, who learned from NASA experts all about NASA's lunar exploration efforts. NASA giveaways included NASA stickers, buildable Moon globe, 3 NASA posters, and NASA technology fliers. Fans got to hold real meteorites, touch Moon and Mars rocks, see up-close an actual Apollo 17 Moon rock, and interact with Solar System Treks—a free, online, lunar and planetary visualization tool on display. Fans also had the opportunity to learn about Ames' Sports-related Technology Spinoffs (eg. the NASA tech being used in Football helmets and high impact shoulder pads), and commercial opportunities within the Tech Transfer program.

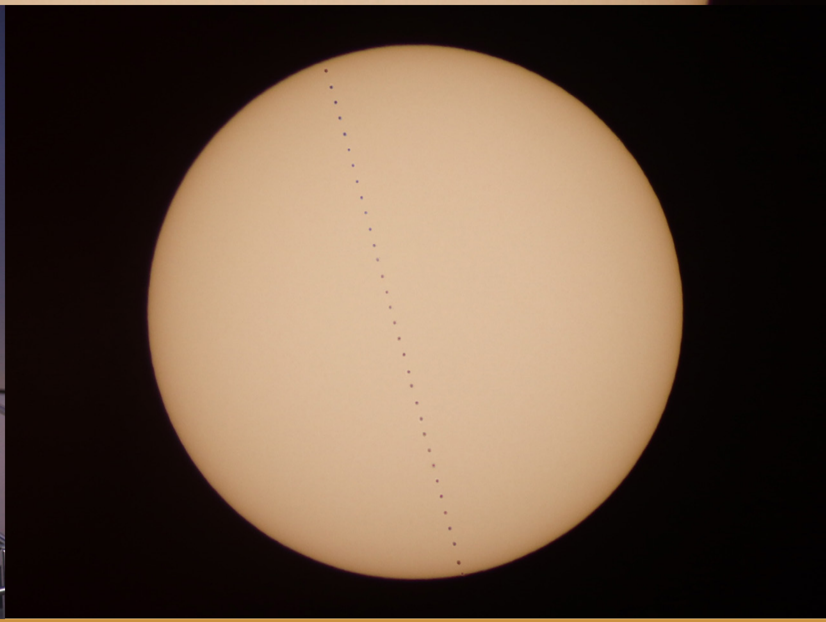
JOURNEY THROUGH THE UNIVERSE, BIG ISLAND, HAWAII

SSERVI participated in Journey Through the Universe, a Gemini Observatory program which reaches over 8000 students annually. Two staff members visited over 30 classrooms, attended a public family event and an astronomy lecture night, directly reaching approximately 1200 students and members of the public.

MERCURY TRANSIT



Emily Law and Brian Day presenting at the Phillip and Patricia Frost Museum of Science and Planetarium in Miami.



Composite image of Mercury transit captured in Brian Day's live stream from his telescope at the Frost Museum.

On Monday, November 11, 2019, SSERVI partnered with the Phillip and Patricia Frost Museum of Science and Planetarium in Miami, Florida to conduct a public program highlighting that day's transit of the planet Mercury around the Sun and the release of the new Mercury Trek portal of SSERVI's SSTP. The museum's location in the southeast corner of the country gave it an ideal vantage for seeing the transit both in terms of the position of the event in the sky and in terms of weather. Brian Day and Emily Law represented SSERVI and coordinated with the the Frost Museum as well as with Gary Varney from the Amateur Astronomy Selenology Project. Frost provided an exhibit hall with a large screen and projector, and space on their roof for the SSERVI team to set up a solar telescope and video camera. The view through the telescope was transmitted down to the screen inside the museum, alternating live views of the transit with guided tours of the surface of Mercury using Mercury Trek.

The program was viewed live at the Frost museum by an audience of 1,500 visitors of all ages, and streamed live over SSERVI's YouTube channel. NASA's new Mercury Trek portal was specifically requested by JAXA, in support of the current joint JAXA/European Space Agency BepiColombo mission to Mercury and features data returned from NASA's MESSENGER mission. The program was augmented by recorded video messages from NASA's Chief Scientist, Jim Green, NASA's Planetary Science Division Director, Thomas Zurbuchen, JAXA's BepiColombo Project Scientist, Go Murakami, and SSERVI's Director, Greg Schmidt.

SSERVI APOLLO 50TH ANNIVERSARY PRESENTATIONS

Greg Schmidt and Brian Day talking with the audience after presenting at Foothill College's "One Giant Leap" celebration.

Brian Day presenting "Lunar Landing Sites, Past and Future" at the San Francisco Exploratorium.

As we approached the 50th anniversary of the first human landing on the Moon, the SSSERVI Central Public Engagement team looked back at each of the Apollo landing sites and discussed why each site was chosen and what made each site so interesting. Presentations at public events recapped some of the fascinating things we've learned from robotic lunar missions that followed Apollo. Looking ahead, SSERVI also communicated some of the amazing sites NASA is considering for future missions to the Moon. Additional SSERVI Central Public Engagement highlights in 2019 included:

Presenting "One Giant Leap Apollo 11 50th Anniversary Panel at Foothill College; "Lunar Landing Sites, Past and Future" to an audience of ~150 at Henry Cowell Redwoods State Park in Felton; Presenting the 2024 Artemis mission to send humans-- and the first woman-- back to the moon at the Grand Mesa Arts and Events Center in Cedaredge, Colorado; Giving two presentations at the Exploratorium in San Francisco; and as part of Lick Observatory's Summer Series, SSERVI gave two full-house presentations on "Lunar Landing Sites, Past and Future" that were paired with viewing through the Observatory's telescopes.

On July 19, former astronaut and NASA AA Leland Melvin, astronomer Jose Francisco Salgado, Greg Schmidt, and Brian Day provided commentary to the San Francisco Symphony's Apollo celebration concert, "Out of this World" at the Davies Symphony Hall in San Francisco.

TRAIN

Nothing is more important than developing the next generation, and for over a decade a foundational element of SSERVI has been training the next generation through a host of research-centered activities. At its heart, SSERVI research solicitations encourage postdoctorate and student participation and funding as a core part of the greater research team. In addition, SSERVI has a history of funding one to two post-doctorate positions at a time through the NASA Postdoctorate Program (NPP) via SSERVI Central; these positions are designed to bridge the work of 2-3 SSERVI teams and thus accelerate collaborative inter-team activities. SSERVI Central has also supported graduate student field training efforts at both Barringer Crater (Arizona) and the Sudbury Impact Structure (Ontario). SSERVI Central provides training to teachers (including lunar sample certification) and co-hosts and supports student challenge events for all ages, and is proud to support the dissemination of materials for the sight-impaired through its series of “Getting a Feel” tactile books. The following section highlights selected contributions from the Central Office in support of training the next generation in 2019.

NPPs SUMMARY

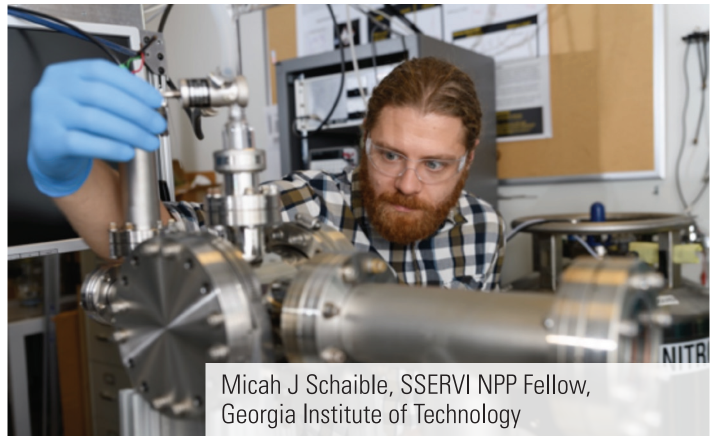
The NASA Postdoctoral Program (NPP) provides early-career and more senior scientists the opportunity to share in NASA's mission. SSERVI NPP fellows are funded to join together multiple SSERVI teams through their research and outreach activities. In 2019, SSERVI funded two NPPs. Their projects are summarized on this page.

Midhun S. Menon, SSERVI NPP Fellow, University of Colorado, Boulder

VIRTUAL REALITY SIMULATOR FOR LUNAR TELEROBOTICS RESEARCH

SSERVI NPP Fellow Midhun Menon at the University of Colorado, Boulder is developing a simulation framework which generates photometrically accurate lunar virtual environments based on available data from remote-sensing satellites and terrain observations from landed missions. The framework renders the environment using the Unity game engine and tightly integrates with the Robotic Operating System (ROS) to simulate robots interacting with the environment. This kind of a modular architecture makes the framework scalable and facilitates performance testing of robotic systems under various adversarial conditions.

Future space missions and activities will increasingly rely on robotic systems that can assist with human missions or aid in teleoperated precursor missions. Virtual planetary environment simulators and testbeds will be pivotal in algorithm design/testing, operations planning, operator training and mission mock-ups. Simulators can act as virtual analogs, thereby facilitating rapid and cost-effective ways to generate large, diverse and realistic testing and training datasets. This will lower barriers posed by hardware and logistics, and pave the way for faster development cycles. This VR simulator can be used to develop robust algorithms for navigation, teleoperation, assembly and deployment of antennas nodes using a rover, and results from this research will be used in designing semi-autonomous navigation and teleoperation assistive algorithms specific to the Moon.



Micah J Schaible, SSERVI NPP Fellow, Georgia Institute of Technology

LOW ENERGY ELECTRON AND ELECTROSTATIC CHARGED DUST GRAIN INTERACTIONS WITH BIOMOLECULE FILMS

SSERVI NPP Fellow Micah J Schaible at the Georgia Institute of Technology is working with the REVEALS, IMPACT, and LEADER (formerly DREAM2) SSERVI teams, to study how electrostatically charged grains can transfer their excess electrons to molecular film analogs of lung cell walls. Electrostaticly charged dust grains can damage biologic tissues and sensitive electronics, and pose a significant risk during exploration activities on bodies such as the Moon. This work will help us understand the potential toxic effects of space dust.

In collaboration with the REVEALS and IMPACT teams, Schaible constructed a novel high vacuum system at Georgia Institute of Technology which is capable of charging dust grains and bringing them into contact with special cell wall analog films. Dust simulants, obtained from the SSERVI CLASS team, are electrostatically charged either through tribocharging or through exposure to electrons from a hot filament source. Grains are then dropped through small holes in the dust cup and allowed to fall onto the films. Before and after exposure to the dust grains, the films are analyzed using a variety of microscopy and spectroscopy techniques to characterize the effects of grain exposure on the film integrity. Additionally, Schaible is coordinating efforts with the SSERVI RIS4E team, who are performing similar experiments to understand grain surface reactivity, and ongoing collaborations with the LEADER team are investigating grain discharging and surface passivation through exposure to various low-pressure gas environments. This work will illuminate fundamental mechanisms of electrostatic charging of regolith grains in space to help develop risk mitigation strategies for space exploration.

NASA LUNAR AND METEORITE SAMPLE CERTIFICATION WORKSHOP

SSERVI staff are certified Apollo Education Sample Curators which authorizes them to conduct certification workshops for K-12 teachers. This certification gives educators the requisite credentials to borrow NASA Apollo lunar and meteorite sample Education Disks. Teachers are shown how to examine material from the Moon, Mars, and asteroids, and are taught the science of astromaterials, curation and educational applications.

Teachers in Hilo, Hawaii, pose with SSERVI staff as part of a collaboration with Gemini Observatory's Journey Through the Universe program that hosted the certification workshop.

TOUCHABLE ROCKS

SSERVI has developed a special encasement for space rocks that allows people to touch the rocks while viewing them under magnification. For the Apollo Anniversary, SSERVI created 28 Touchable Moon and Mars Rock displays which were provided to SSERVI teams and offered to museums across the country and around the world (teams and museums inserted their own samples into the display). They can be seen on display in prestigious museums including San Francisco's Exploratorium and Fondazione Museo Civico di Rovereto in Italy.

ROBORAVE

27 countries are now part of RoboRave International, with more countries joining the event each year. For over 8 years SSERVI has been active in cultivating this exciting robotics community, participating as an invited keynote speaker at the 2019 World competition held in Albuquerque, New Mexico, and as a speaker at their Robotic Teachers Academy in NM in May, 2019. SSERVI was also a keynote speaker and presentation judge at RoboRave California at the Santa Clara Convention Center in June, 2019. In addition, SSERVI was an invited keynote speaker as guest of the Mayor of Kaga City at the 5th RoboRave in Kaga City, Japan in November. The official partnership between SSERVI and JAXA signed in July 2019 facilitated an expanded role in developing a robotics workshop and starting an industry day and education round table with JAXA and key government officials in Kaga City. SSERVI coordinated and co-planned these two new events, and because SSERVI's invitation for JAXA participation was so successful, the Japanese Space Agency agreed to be a sponsor for future RoboRaves in Kaga City.

NASA 3D HABITAT CHALLENGE

NASA and its partners held a $3.15 million competition to build a 3D printed habitat for the agency's journey to Mars or deep space exploration. The multi-year, multi-phase challenge is designed to advance the construction technology needed to create sustainable housing solutions for Earth and beyond. SSERVI has a long history of supporting the NASA Centennial Challenge going back to 2008-2009 NASA Robotic Mining Challenge. In 2009 SSERVI hosted the Robotic Mining Challenge at Ames Research Center. SSERVI not only supported the competition and assisted in creating the annual college-level spin-off Robotic Mining Competition at Kennedy Space Center. From 2015-2019 SSERVI supported and has judged the 3D Habitat Challenge as teams demonstrate many different additive manufacturing technologies, from design to software modeling to physical construction. The unique challenge was competed in three phases: design, structural member, and on-site habitat construction. More than 60 teams participated, and NASA awarded over $2 million in prize money.

REGOLITH MINING COMPETITION

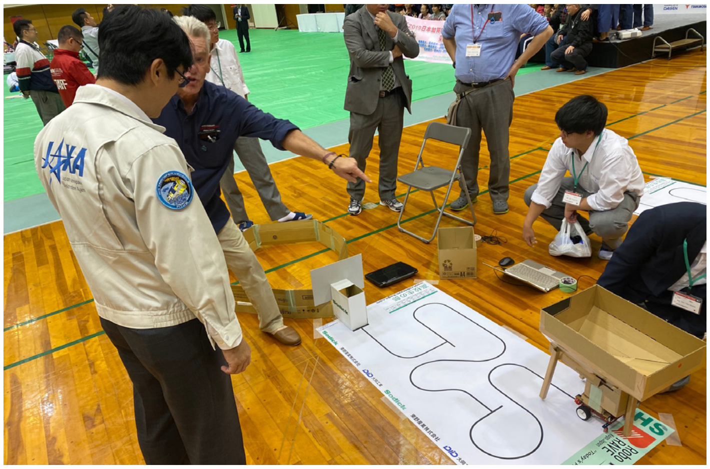
NASA is going back to the Moon with water and resource utilization as a key theme before then going on to Mars. Capturing water at the lunar poles is key to allowing humans to "live off the land" as it will be used for human consumption, hygiene, growing plants, providing radiation shielding and to make rocket propellant for the journey home.

The NASA 3D Habitat Challenge at the Caterpillar Edwards Demonstration and Learn Center located in Peoria, Illinois.

NASA's 2019 Robotic Mining Competition challenges university-level students to design and build mining robots that can traverse the challenging, simulated, off-world terrain. Due to the U.S. Government furlough, Caterpillar Inc. agreed to host the competition at the University of Alabama in May. SSERVI staff judged contestants as they excavated icy-regolith simulant (rock/gravel) and returned the excavated mass for deposit into a collector bin to simulate an off-world, In Situ Resource Utilization mining mission. NASA directly benefits from the competition, and the development of innovative robotic excavation concepts. Every year NASA receives over 40 proof-of-concepts which are often clever solutions that may be applied to an actual excavation device or ISRU mission payload.

SSERVI's Joseph Minafra delivering keynote talk with JAXA's Mr. Kamimori (aka "No limits") and translator Mr. Naofumi (Fumi) Hayashi.

Two Regolith Judges set up final display with the two winning excavators showing radically different designs.



The founder of RoboRave International explains the Line Following competition to Kamimori, the Director of Management and Integration Department Human Spaceflight Technology Directorate of JAXA.

BOOKS FOR THE BLIND

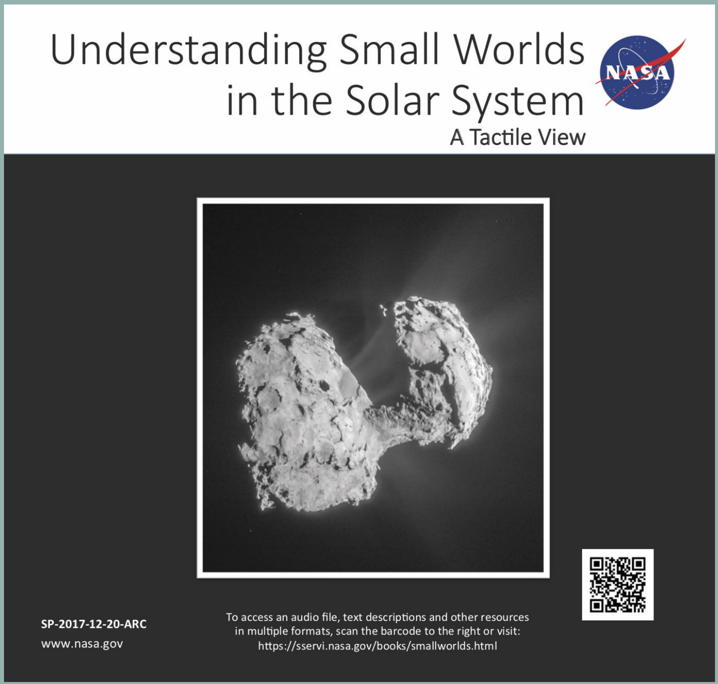
For the sighted, events like the recent 2017 and 2019 solar eclipses are experienced through a combination of multiple senses, not just sight. For people who are visually impaired or blind, the experience is different. While they may sense changes in the intensity of the sunlight, temperature, and animal noises, they are unable to "see" what is happening. To bring this remarkable experience to life for them, two education and public engagement teams from SSERVI's Center for Lunar and Asteroid Surface Science (CLASS) and SSERVI Evolution and Environment of Exploration Destinations (SEEED), developed two tactile books. *Getting a Feel for Eclipses* and *Abre Tus Sentidos a los Eclipses – Sudamérica*, provide users who are blind or visually impaired a means to see and experience a total solar eclipse through their fingertips. Similarly, another new tactile book, *Getting a Feel for Lunar Craters: Apollo 50th Commemorative Edition* brings the lunar surface to life with background information and graphics on how the surface formed and evolved and a bit about the Apollo program and future exploration. *Understanding Small Bodies in the Solar System* provides a look at several moons, comets and asteroids in our solar system. The unique, hand-made, tactile graphics are created from various textured materials such that each feature is readily identified. A QR code associated with each book provides access to digital content describing each tactile and associated background information. Through this delivery mechanism, sighted and unsighted may access the content with any smart device.

"Understanding Small Worlds in the Solar System"

This book, explores small bodies found in our solar system-- typically asteroids or comets, but interplanetary dust, Kuiper Belt Objects, material in the Oort Cloud, planetary satellites and, yes, even Pluto and other dwarf planets are considered "small bodies."

"Getting a Feel for Lunar Craters Apollo 50th Commemorative"

Written and edited by Cassandra Runyon (College of Charleston), David Hurd (Edinboro Univ. of Pennsylvania) and SSERVI's Joe Minafra, this new commemorative edition of the popular *"Getting a Feel for Lunar Craters"* includes a bit of history on America's Apollo spacecraft and the astronaut's spacesuit.



2019 South American Eclipse Addendum

As a special addendum to *"Getting a Feel for Eclipses"* this tactile guide details the 2019 and 2020 total solar eclipses in Chile and Argentina. Tactile graphics in the book provide an illustration of the alignment of the Sun with the Moon and the Earth, the developing stages of the eclipse, and a map of Central and South America labeled with the 2019 and 2020 paths of totality.

The total solar eclipse of July 2, 2019 darkened the sky for thousands along the eclipse path in Chile and Argentina. The 'diamond ring' effect is seen here at the end of the eclipse, with the Andes mountains below. Credit: Greg Schmidt

CONNECT

Working virtually – bridging geographical gaps to create teams that thrive despite the distance separating their members – was an experiment for NASA years ago, but through SSERVI and other efforts it is now becoming more and more mainstream. Facilitating multiple, distributed teams working together on new, interdisciplinary science and exploration efforts is an essential part of SSERVI. But going beyond that and getting teams to truly collaborate across a heavily distributed network is where the real magic occurs. Virtual collaboration platforms – video and beyond - allow the sharing of ideas and information between disparate collaborators to work towards a common goal. SSERVI Central's Tech team produces numerous virtual meetings, develops tools and technologies that facilitate remote collaboration, and are recognized throughout NASA and the community as experts in their domain. Production of these meetings, ranging from the relatively small SSERVI EC to conferences with hundreds of attendees, is a skill set garnered only through experience in a wide variety of settings, using a multitude of tools. In addition, the Tech team keeps a pulse on the latest state-of-the-art computer technology, actively researching, reviewing, and testing new tools, to find those best suited for each virtual collaborative encounter.

SSERVI's Tech team supports the virtual distribution of presentations at large conferences, webinars, workshops without walls, seminar series, and group-to-group and person-person meetings. In addition, they address any problems that arise with the technology, and proactively work to remove barriers to collaboration by imparting the science teams with knowledge they need for any virtual collaboration media selected, so they understand how to use the virtual collaboration technology and can perform their tasks efficiently with lower frustration levels. This way, technology-mediated collaboration between virtual team members can be carried out seamlessly via the best communication tools available.

VIRTUAL COLLABORATION

SSERVI integrates and implements information technology tools to connect the distributed institute teams and the greater planetary science and exploration communities. Virtual collaboration platforms facilitate communication, collaboration, and the digital delivery of content, promoting the sharing of ideas and information between disparate collaborators to work towards a common goal. The technologies SSERVI utilizes include high-fidelity video-conferencing, real-time meeting and communication platforms, websites and dynamic web applications, online communities, social networks, shared databases, data visualization applications, and mobile devices. SSERVI also focuses on researching user-experience improvements and integrating new capabilities that further enable and enhance accessibility.

Event Production

SSERVI Central's Tech Team led the production and delivery of 24 events with over 338 presentations that were broadcasted live and made available for on-demand playback. This valuable service makes important information widely available to the community, with over 7,200 live-stream views and nearly 133,000 views of recorded sessions. Most notably, NASA Administrator Jim Bridenstine's keynote address to the Planetary Defense Conference has over 125,000 playbacks alone! Of these events, 18 were in direct support of SSERVI's domestic Teams while 7 events supported SSERVI affiliated organizations both in and out of NASA. SSERVI continues to receive praise in its multimedia content delivery and technical production capabilities.

Some of the main events included:

1. The 2019 NASA Exploration Science Forum, which produced 65 recorded presentations with 669 live views and 2610 on-demand playback views. In addition, SSERVI hosted a panel on the USS Hornet as part of the Apollo 11 50th Anniversary celebration and webcast from the ship.

2. The 2019 Planetary Defense Conference is held every two years. There were 109 presentations recorded over 5 days, which included 4,870 live views, and 131,807 views of the recorded content.

3. The 2018 Annual Meeting of the Lunar Exploration Analysis Group recorded 30 presentations with 989 live views and 905 on-demand playback views.

4. SSERVI produced the live broadcast and streaming of the 20th and 21st Meetings of the NASA Small Bodies Assessment Group. The two multi-day events accrued a total of 2239 live views and 678 on-demand playback views.

5. There were 11 CLASS Seminars and Journal Club meetings totaling 157 live and 146 on-demand views.

6. The Centaur Exploration Workshop was viewed by 303 live and 485 on-demand playback views.

7. Other support included: Analog Focus Group Seminars.

Unified Communications & Collaboration

Enabling collaboration and communication across multifaceted teams and community members remains at the forefront of SSERVI's Information Technology scope. Given the rate at which new technologies become available, SSERVI continues to evolve in evaluating, integrating, and architecting capabilities that grow collaboration. In the past year, SSERVI explored new hardware, software, and collaboration practices that serve as the foundation for a more rich user-experience. In addition, SSERVI has provided insight and guidance to numerous Agency organizations and teams to increase the awareness and effectiveness of collaboration technologies while supporting virtual events as requested.

WEB & INFRASTRUCTURE

To further the reach of the groundbreaking science and research that SSERVI teams and affiliates release, the sservi.nasa.gov website is updated regularly with news and discoveries, while auxiliary websites and web applications are developed and maintained for relevant events and community members. The SSERVI Central Web Team continued to push forward-thinking web architecture when developing and deploying dynamic websites and web applications. These new approaches are aligned with a more robust, secure, accessible, and effective web experience.

Website	Description	URL
SSERVI	Defining the Institute while highlighting SSERVI research, related science, events/activities, and resources to the community.	sservi.nasa.gov
NASA Exploration Science Forum	Home of the annual NASA Exploration Science Forum (NESF) where users find information on logistics, registration, abstract submissions, and on-demand playback of all presentations.	nesf2019.arc.nasa.gov
SSERVI Awards	The SSERVI Awards website highlights past winners of the distinguished Shoemaker Medal, and the Wargo, Niebur, and Coradini Awards, while allowing the community to nominate candidates for the yearly distributed awards.	sservi.nasa.gov/awards
SSERVI Books	The SSERVI Books website was created to highlight the Institute's literary efforts, including books for the blind such as "Getting a Feel for Lunar Craters" and "Getting a Feel for Eclipses"	sservi.nasa.gov/books
European Lunar Symposium	The European Lunar Symposium (ELS) website provides users with logistics, registration, and abstract information related to this annual event.	els2019.arc.nasa.gov
Centaur Exploration Workshop	A workshop addressing the scientific importance and space exploration relevance of active centaurs, with a specific focus on mapping knowledge gaps and paths forward. CEW website provides users with logistics, registration, and abstract information.	cew2019.arc.nasa.gov
Carbon in the Solar System	A workshop addressing the topic of Carbon in the Solar System with talks on observational, lab and modeling work related to carbon and carbonaceous species on Solar System bodies.	carbon-workshop.arc.nasa.gov/
SSERVI Focus Groups	SSERVI hosts researcher-led Focus Groups on a wide variety of topics. Some groups host seminars and those recordings are archived on the website for on-demand playback.	sservi.nasa.gov/focus-groups/
Ames Collaboration Team	SSERVI has provided the Ames Collaboration Team with an event scheduler application which records all events to a database while also automatically scheduling the events to a central calendar.	For Internal Use Only
URL Shortener	SSERVI continued to support a tailor-made URL shortener with analytics that has been used across the agency.	For Internal Use Only

Websites developed and managed by SSERVI Central.

ACKNOWLEDGEMENTS

Many people have contributed to SSERVI's successes in 2019. We would like to start by thanking our strong supporters at NASA Headquarters for their leadership, funding and guidance: Dr. Lori Glaze, Dr. Sarah Noble and Dr. Shoshana Weider from the PSD of the NASA SMD, Kristen Erickson from the Science Engagement and Partnerships Division of SMD, Dr. Paul Hertz from the Astrophysics Division of SMD; Jason Crusan, John Guidi, Dr. Ben Bussey (now in SMD), Dr. Jake Bleacher, Dr. Bette Siegel, and Victoria Friedensen from the NASA HEOMD; and Dr. Jim Green, the NASA Chief Scientist.

We gratefully acknowledge continued support from NASA Ames Research Center Senior Leadership, ARC grant specialists, and mission support services. In particular, we thank Ben Varnell for his expert financial support over the last decade, assisted by Michael Baumgarten, and Barrie Caldwell and Bea Morales for their unwavering support of the many SSERVI procurement activities since the institute's founding. SSERVI's leadership in online technology is facilitated by its close collaboration with the IT resources and expertise of NASA Ames Research Center – NASA in Silicon Valley. We also extend our gratitude to the Code S IT staff, in particular Chris Wilson, for their expert support.

In 2019, the Apollo 50th anniversary was celebrated worldwide. Today, the ongoing efforts of SSERVI's domestic research teams, its international partners, and the broader research community with whom we work so closely, are deriving new revelations from the data and samples returned by Apollo. In 2019, NASA renewed its focus to return humanity to the Moon through the Artemis program. We proudly acknowledge the key roles that SSERVI's teams, international partners, and many collaborators in the lunar community are taking on to enable this next great adventure. We acknowledge with special gratitude the many remarkable achievements of the SSERVI CAN-1 teams who completed their programs with us in early 2019. We also thank the new CAN-3 teams, who began their new programs later in 2019, for their fresh infusion of exciting, new, innovative techniques and avenues of research.

SSERVI is grateful to work alongside so many international researchers helping to lead a global effort towards an expanded human presence in space. We would like to particularly thank Mahesh Anand at the Open University for his leadership of the European Lunar Symposium, Gordin Ozinski at the University of Western Ontario for spearheading many field training excursions, and other international partners who participate in SSERVI meetings and activities and provided input into this report.

SSERVI is proud to recognize the advances made by the Solar System Treks Project team at JPL under the leadership of Emily Law. This year, an enhanced Treks suite provided new characterization capabilities for lunar sites of interest, and expanded coverage to include additional planetary bodies. These new tools and capabilities have resulted in additional collaborations within the agency, the agency's international and commercial partners, and the planetary science community.

The management of SSERVI gratefully acknowledges the work of the staff of SSERVI's central office in facilitating all of the above accomplishments.

Finally, we acknowledge all of our friends in the lunar science and exploration community. Your dedication, tenacity, and endurance have sustained the field through the lean years, reinvigorated the field today, brought forth a new generation of brilliant researchers and explorers, and taken us to the brink of humanity's sustained presence on the Moon and beyond.

Ad lunam, ad astra!

SSERVI U.S. TEAM EXECUTIVE SUMMARY REPORTS

Executive Summaries of Team Reports

The executive summaries of the 2019 team reports provide a high level look at some of the team accomplishments enabled by SSERVI. These selected highlights briefly touch upon some of the important topics covered in the team reports and give a flavor of the activities and impact of each individual team. Cross-team collaborations, international partnerships, student involvement, and mission experience are topics covered in much greater detail in the full reports that follow.

CAN 1 Teams (2014-2019)

The Center for Lunar and Asteroid Surface Science (CLASS) team led by Dr. Dan Britt at the University of Central Florida studies the interaction between the surfaces of airless bodies and the space environment, exploration activities, and potential resource exploitation. Our research includes measuring and observing the physical and thermal properties of regolith material, observations of mineralogy of primitive asteroids, the behavior of regolith in lunar and microgravity, the chemical reactions and reaction products that are part of space weathering, combined radar and optical characterization of asteroid surfaces, the cohesive forces on small asteroids including the interparticle forces and charging, analysis of the cohesive properties of meteorites, asteroids and bolides, and the use of regolith as a resource for construction, fuel, and life support consumables. CLASS has several node-wide initiatives including on-line advanced planetary science education with 5 graduate-level seminar courses recorded for community access, the CLASS Exolith Laboratory which is the world leader in the development and production of lunar and asteroid regolith simulants, and the CLASS Planetary Landing Team which brings together the world's experts in rocket plume dynamics and surface interactions with the leaders of the growing commercial landing industry. CLASS is fundamentally an organization to bring the best science into the service of lunar and asteroid exploration.

The Center for Lunar Science and Exploration (CLSE) team led by Dr. David Kring at the USRA Lunar and Planetary Institute and NASA Johnson Space Center studies impact history and processes, geochemistry of regolith, including volatile components, and ages of regolith materials on the Moon and other airless bodies. The team announced in January 2019 that they may have discovered Earth's oldest rock in an Apollo 14 sample, a product of the collisional exchange of material between the Earth and Moon about 4 billion years ago. Continuing to probe that collisional epoch further, the team reported that impact melts in Apollo 16 samples were produced by multiple impact events about 4 billion years ago, supporting the concept of an intense period of bombardment at that time. The team showed that impact cratering is the dominant process that shaped the lunar south pole, the next destination for human explorers. Using the team's expertise with that type of geologic terrain, CLSE began to evaluate landing site and EVA options for crew and robotic assets engaged in the Artemis program. Trafficability conditions in two types of ISRU-relevant terrains were conducted: for pyroclastic deposits and permanently shadowed regions where volatiles may be stored. Model calculations were developed to predict the distribution of volatiles in the vicinity of the south pole and the potential tonnage of ice resources being sought for a sustainable exploration program.

The Dynamic Response of Environments at Asteroids, the Moon, and Moons of Mars (DREAM2) team led by Dr. Bill Farrell at Goddard Space Flight Center (GSFC) examines the complex three-way interaction between the harsh space environment, the exposed surfaces of airless bodies, and human systems near these affected surfaces. During its sixth calendar year of 2019, the team was primarily on a no-cost extension (NCE) from March 2019 until Mid-October 2019, and at that time operations transferred over to the new SSERVI/LEADER team (awarded in Can-3). Even under the abridged year, the team had considerable momentum and carried out a number of studies in support of the new exploration initiatives. The team author/coauthored 24 published or submitted papers on the space environment at airless bodies, including the Moon. In May 2019, the team also was awarded the prestigious Robert H. Goddard Award for excellence in science, being specifically cited ‘For excellence in the application of space environmental science to exploration applications.’ In the area of surface interactions, the team modeled the lifetime of frost in polar craters – suggesting the top layer sensed by LRO/LAMP is less than 10,000 years old. They also performed joint GSFC-JSC laboratory studies on the electrical dissipation of space suit materials using the DREAM2 beam line in GSFC’s unique Radiation Effects Facility. In the area of space plasma interactions, team members were part of a comprehensive study defining the character of the trailing lunar wake region as sensed by the THEMIS-ARTEMIS spacecraft using over 7 years of data in their statistical analysis (there is no comparable study of its kind). Early career team members working on space plasmas also contributed substantial works on plasma waves associated with lunar magnetic anomalies and of a possible ion torus at Phobos. In the study of exospheres at airless bodies, team members were involved in a study suggesting the Sun had to be a slow rotator over the last 4 billion years to account for the amount of volatiles sodium and potassium remaining in the regolith. They also re-examined ALSEP/LACE data specifically targeting the change in the noble gas Neon exosphere during solar disturbed periods. In the study of the radiation environments, team members presented a new index of Solar Energetic Particle events as derived from the LRO/CRaTER measurements for use by the community and re-estimated the permissible mission duration of astronauts in the weakening solar environment. These two activities are among the most critical DREAM2 analysis in support of human exploration – a truly unique contribution to exploration endeavors. In the area of lunar exploration, team members supported EVA studies with our JSC partners and assisted in defining environmental requirements with our MSFC partners. Many team members are involved in the CLPS program in the build of payloads to be carried by commercial landers in the 2021-2022 timeframe – with DREAM2 studies providing science justification for some of these payloads. To assist in enabling this array of exciting basic science and exploration application research, DREAM2 continued to support an outstanding intern program— with many students from a Howard University-DREAM2 collaboration established in 2013. The team continues to integrate many post-doctoral fellows and graduate students at Goddard and at partnering institutions. DREAM2 also works in close coordination with our SSERVI partnering teams (eg. VORTICES, IMPACTS and REVEALS), especially in the areas of surface interactions and exospheric research. Working with SSERVI-Central, we act to merge this shared expertise across teams triggering many new joint research projects.

FINESSE (Field Investigations to Enable Solar System Science and Exploration) is an interdisciplinary team of scientists, technologists, and mission operations specialists focused on conducting field-based research to understand geologic processes on the Moon, asteroids, and Phobos & Deimos while simultaneously preparing for future human and robotic exploration of these destinations. FINESSE is led by Principal Investigator (PI) Dr. Jennifer Heldmann and Deputy PIs Drs. Darlene Lim and Anthony Colaprete of NASA Ames Research Center. FINESSE includes team members from government, academia, and industry, including both domestic and international partners. We operate under the philosophy that “science enables exploration and exploration enables science.” FINESSE fieldwork has focused on a variety of volcanic and impact processes relevant for the Moon and other Bodies. FINESSE research has also focused on optimizing human operations in planetary environments. Significant research efforts and findings have been reported on the following topics based on high-fidelity analog field testing: field portable instrumentation; communications (bandwidths & latencies); EVA technologies; mission support architecture (EVA, IV, Earth); required datasets for pre-, during, and post mission use; scheduling and timelining tools; traverse planning tools and procedures; sample collection assessment and protocol; and UAS (uncrewed aerial systems) for science data collection and field exploration support. We have established a new terrestrial analogs laboratory at NASA Ames Research Center (PLANETAS: PLANetary Exploration Through Analog Science) where FINESSE field and laboratory instrumentation, including but not limited to, visible-near infrared spectrometer, x-ray diffraction spectrometer, laser induced breakdown spectrometer, high temperature ovens, precision scales, etc., are housed for science and exploration use. We have utilized multiple field deployment platforms for instrumentation, including drones and high-altitude balloons, and have been pioneering the use of Virtual Reality (VR) and Augmented Reality (AR) systems to enable scientific measurements and analysis of analog features as well as examine the use of VR/AR systems for future astronaut training and planetary surface operations.

The Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT) Team led by Prof. Mihaly Horanyi at the University of Colorado Boulder continued its experimental and theoretical investigations of the effects of high-speed meteoroid impacts, plasma and ultraviolet (UV) charging, mobilization and transport of dust due to human/robotic activities and natural processes on the physical, chemical and geotechnical properties of regolith surfaces. IMPACT made significant contributions to gauging the effects of hypervelocity dust impacts and dusty plasma processes operating on the lunar surface on the accumulation, transport and accessibility of water and other volatiles for In-Situ Resource Utilization (ISRU). Our research program remains focused on safeguarding the journey and sustaining the presence of humans in space, on the lunar surface, and eventually Mars.

The Institute for the Science of Exploration Targets (ISET) Team led by Dr. Bill Bottke at the Southwest Research Institute uses state-of-the art modeling, combined with interpretation of spacecraft data, to reveal what the Moon, Phobos and Deimos, and asteroids can tell us about the origin and evolution of the Solar System, thus establishing critical scientific context for future exploration of these objects. ISET research comprises four themes. In Theme 1, “Formation of the Inner Solar System and the Asteroid Belt,” we used the uniquely powerful accretion and fragmentation code LIPAD to track the growth of the inner planets, finding that pebble accretion may have played a pivotal, heretofore unrecognized role in sculpting Mars and establishing the asteroid belt’s properties. We evaluated how giant impacts affect planet formation, and how pebbles trapped in resonances with the planets affect their migration within a gas disk, and thus the site and chemical conditions of their formation. In Theme 2, “Origin of the Moon and Phobos/Deimos,” we developed a state-of-the-art model for tracking lunar accretion beyond the Roche limit, which can be used to accurately model how a disk produced by a giant impact with the Earth relates to the initial dynamical, chemical, and thermal states of a moon that accumulates from the disk, thus establishing how observable properties of the Moon relate to its mode of origin. We developed new models to evaluate whether a solar resonance could have removed substantial angular momentum from the early Earth-Moon system, as implied by leading giant impact models developed by us and others. We also explored how the impact of large, differentiated projectiles onto early Mars could account for isotopic inhomogeneities in Pt and W observed in martian meteorites. In Theme 3, “The History of NEAs and Lunar Bombardment,” we examined how bombardment of the Earth by asteroids 3.2-3.5 billion years ago may have jump started plate tectonics. We also studied bombardment of the Moon over the last several billions of years, finding that there appear to be impact spikes at particular times in its history. We probed the early bombardment of Vesta and Ceres, identified a major new crater under the ice in Greenland, and potentially identified the parent body of the H chondrite meteorites. In Theme 4, “NEAs: Properties, Populations, New Destinations,” we continued research on the effects and implications of non-gravitational forces and weak cohesive bonds within primitive Solar System bodies relevant to future exploration of NEAs. We explored the granular mechanics of rubble pile bodies when cohesion is present, the dynamical evolution of small bodies under the effect of non-gravitational forces, and specific studies of near-Earth asteroids and their dynamics when subject to close flybys.

The Remote, In-Situ, and Synchrotron Studies for Science and Exploration (RIS^{4}E) team led by Dr. Tim Glotch at Stony Brook University uses advanced field, laboratory, modeling, and remote sensing techniques to enable the safe and efficient exploration of the Solar System and to maximize the science return from missions to airless bodies in the Solar System. In closing out RIS4E activities over the last year, the team has, among other projects: (1) tested the ability of simplified and complex light scattering models to accurately model the spectra of space weathered particles at visible/near-infrared wavelengths, (2) completed the first ever calculation of the mid-infrared optical constants of a geologically important triclinic mineral, (3) begun the construction of a new machine learning-based taxonomy for asteroids based on visible and infrared spectra, (4) used ground-based LiDAR measurements to determine the eruption history of the Kilbourne Hole maar crater, (5) determined the dissolution rate of olivine in simulated lung fluid at human body temperature, (6) investigated the interaction of macrophage cell cultures with lunar soil simulants, and (7) used synchrotron nano-IR spectroscopy and imaging to investigate fine-scale mineralogy and organic speciation in an H5 ordinary chondrite.

The SSERVI Evolution and Environment of Exploration Destinations (SEEED) team was able to continue selected science and exploration activities through 2019 at a significantly reduced level by carefully directing unspent funds into areas most commensurate with our primary themes: chemical and thermal evolution of the Moon and small bodies, origin and evolution of volatiles, regolith issues in airless environments, and science and engineering synergism as lunar exploration blooms. Our priorities focused on probing and communicating science issues, as well as training the next generation of leaders in this field. Example highlights during this period include: [A] evaluating cross-cutting roles of Ti (ilmenite) in lunar geochemistry: magma ocean evolution, constraints on the source region of mare basalts, and new tools to study unsampled basalts with spectroscopy; [B] accurate modeling of highly unusual circular features observed in clusters on the Moon to assess their origin and implications for lunar volcanic history; [C] integration of remote sensing data for the lunar south pole region to illustrate that the bulk composition is dominated by feldspathic ‘highland’ material (similar to that sampled at Apollo 16); [D] examining evidence that constrains the age of Mercury’s polar ice to be recent deposits and implications for the Moon; [E] evaluation of returned samples to show that lunar space weathering processes occur rapidly (<2 Ma) and require redistribution of surficial iron (e.g., by micrometeorites); [F] assessing the geology and three-dimensional structure of Marius Hills, one of the most prominent lunar volcanic complexes; [G] documenting geologic and engineering constraints at Mons Malapert, a prominent South Pole high illumination site. Public Engagement highlights include: (a) a well-attended and enthusiastic Microsymposium 60 ‘Forward to the Moon to Stay: Understanding Transformative Lunar Science with Commercial Partners,’ (b) a local RI Robotic Block Party (day-long science demonstration/discussion with all ages), (c) a highly successful week long Apollo 50th celebration in Providence including a special ‘Touch the Moon’ interaction allowing participants to touch an actual piece of the Moon (certified lunar meteorite), (d) continued co-sponsorship of another stimulating student-initiated “Space Horizons 2019” (A Century in Space: Designing 2056) [also part of our Science and Engineering Synergism theme].

The Volatiles, Regolith and Thermal Investigations Consortium for Exploration and Science (VORTICES) team, led by PI Andrew Rivkin and Deputy PIs Rachel Klima of the Johns Hopkins University Applied Physics Laboratory, has been carrying out research since 2014 on four broad themes: “Volatiles: Sources, Processes, Sinks;” “Regolith Origin and Evolution;” “Resource Identification;” and “Strategic Knowledge Gap Analysis.” During 2019, work by the VORTICES team spanned a broad range of topics. A study showed that measurements of the diurnal lunar water cycle can be used to gain insight into the source of lunar water and/or its interaction with the surface. A serendipitous multispectral measurement of a lunar impact during an eclipse is being analyzed in order to determine the size and nature of the impactor. Thermophysical modeling of the asteroid Eros from ground-based observations shows that Eros' surface is not homogeneous in its thermal properties. Work has begun looking at machine learning approaches to expanding asteroid taxonomies to wavelength regions not currently used for such analyses.

CAN 2 Teams (2017-2022)

The Project for Exploration Science Pathfinder Research for Enhancing Solar System Observations (Project ESPRESSO) team led by Dr. Alex Parker at the Southwest Research Institute conducts a broad array of pathfinding investigations to identify novel techniques and technologies for enhancing the safety, ef-ficiency, and scientific productivity of human and robotic exploration of the Moon and asteroids. In 2019, the team pioneered the development of magnetic anchoring and sample collection technologies for low-g surfaces, resulting in selection of a NASA Flight Opportunities Program award to demonstrate the performance of two ESPRESSO-developed "Clockwork Starfish" free-flying magnetic regolith sam-pling mechanisms aboard a suborbital rocket in 2020. Further, team members demonstrated that mag-netic anchoring of seismic instruments can deliver extraordinary improvement in acoustic coupling to asteroid interiors over passive gravitational coupling, and implemented a fully-functional prototype of a femtosatellite-scale magnetically-anchored seismic sensor mote that could be inexpensively deployed across asteroid surfaces in advance of anticipated seismic excitation (e.g., the 2029 Earth-Apophis close encounter). These efforts also resulted in further improvements to the team's instrumented impactors for rapid remote terrain stability assessment, which have shrunk to just 40mm in diameter and now in-clude long-range radio transceivers. They also expanded the suite of active spectroscopy methods under development for lunar exploration to include an ultra-low cost handheld fluorimeter instrument that was designed, implemented, calibrated, and field-tested in an extremely rapid development cycle of just two months, and found that UVC fluorimetry was a rapid, robust, and low-cost means of identifying the relative concentrations of common lunar minerals in a field setting. The ESPRESSO team led their first field campaign at the Palisades Sill in New Jersey, testing the application of handheld Raman, LIBS, and fluorimetry instruments for conducting real-time geochemical analysis in a lunar analog setting. Team members were also deployed to Iceland to field-test a laser velocimetry system for remotely tracking 10μm-scale particulate embedded in gas flows, and to southern Colorado to capture a stellar occultation by PHA (3200) Phaethon in support of JAXA's DESTINY+ mission and delivered the most central occul-tation cord of the effort, placing strong constraints on the solid-body size of the object.

The Network for Exploration and Space Science (NESS) team led by prof. Jack Burns at the University of Colorado Boulder is an interdisciplinary effort that investigates: the deployment of low frequency radio antennas in the lunar/cis-lunar environment using surface telerobotics for cosmological and astrophysical measurements of neutral hydrogen at the end of the Dark Ages, during Cosmic Dawn, and at the onset of the Epoch of Reionization; radio emission from the Sun; and extrasolar space weather and exoplanets. NESS develops instrumentation and a data analysis pipeline for the study of the first luminous objects (first stars, galaxies and black holes) and departures from the standard model of cosmology in the early Universe, using low frequency radio telescopes shielded by the Moon on its farside. The design of an array of radio antennas at the lunar farside to investigate the Dark Ages, Heliophysics, and Exoplanet Magnetospheres, is a core activity within NESS, as well as the continuous research of theoretical and observational aspects of these subjects. NESS develops designs and operational techniques for teleoperation of rovers on the lunar surface facilitated by the planned Lunar Gateway in cis-lunar orbit. New experiments, using rovers plus robotic arms and Virtual/Augmented Reality simulations, are being performed to guide the development of deployment strategies for low frequency radio antennas via telerobotics.

The Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS) team lead by Prof. Thomas Orlando at the Georgia Institute of Technology studies solar wind, meteoroid and radiation processing of regolith materials on the Moon and other airless bodies. The team concentrates on understanding the underlying physics and chemistry involved in space weathering and has developed fundamental models with predictive capabilities and novel laser-based state-of-the-art experimental approaches. The team also focuses on modeling and developing solar-mediated in-situ resource utilization (ISRU) strategies for the extraction of volatiles such as molecular water, oxygen and hydrogen for a sustained human presence on the Moon. In addition, a multi-disciplinary effort on developing and testing novel materials for space-suits and active real-time radiation dosimeters is underway. The materials efforts take advantage of the remarkably useful mechanical and electronic properties of nanocomposites and multilayer meta-materials and will help mitigate risks and determine effective EVA operation protocols. Overall, these efforts collectively address a large number of SMD and HEOMD objectives.

The Toolbox for Research and Exploration (TREX) team, led by Dr. Amanda Hendrix at the Planetary Science Institute (PSI), had an extremely productive year in advancing studies of science and exploration at the Moon and asteroids. One aspect of TREX studies focuses on acquisition of a spectral library that is critically needed to interpret spacecraft measurements: reflectance data of fine-particle samples (<10 microns) under environmental conditions at wavelengths covering the ultraviolet through the mid-infrared. In 2019, the team completed measurements of a suite of 28 terrestrial samples, forming the foundation of a spectral library for use by the community and in future TREX analyses; work will begin on measuring meteorite and lunar samples in the coming year. Work in 2019 also ramped up significantly in preparation for field work planned for the spring of 2020: instruments were purchased or developed, including an FTIR, UV spectrometer and GRS. In addition, the laboratory-measured reflectance data have been loaded into the Tetracorder software for real-time autonomous sample selection work in the field. Studies of datasets including LRO and Ryugu have been undertaken by the TREX team to characterize surface composition, hydration levels, and photometric properties for sample acquisition.

U.S. TEAM REPORTS

The SSERVI teams are supported through multiple year cooperative agreements with NASA (issued every 2-3 years) for long duration awards (5 yrs) that provide continuity and overlap between Institute teams. Each team is comprised of a number of elements and multiple institutions, all managed by a Principal Investigator.

CAN-1 TEAMS

Center for Lunar and Asteroid Surface Science (CLASS)
Daniel Britt, University of Central Florida

Center for Lunar Science and Exploration (CLSE)
David Kring, Lunar and Planetary Institute, Houston, TX

Dynamic Response of Environments at Asteroids, the Moon, and Moons of Mars (DREAM2)
William Farrell, NASA Goddard Space Flight Center, Greenbelt, MD

Field Investigations to Enable Solar System Science and Exploration (FINESSE)
Jennifer Heldmann, NASA Ames Research Center

Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT)
Mihaly Horanyi, University of Colorado, Boulder, CO

Institute for the Science of Exploration Targets (ISET)
William Bottke, Southwest Research Institute, Boulder, CO

Remote, In Situ, and Synchrotron Studies for Science and Exploration (RIS4E)
Timothy Glotch, Stony Brook University

SSERVI Evolution and Environment of Exploration Destinations (SEEED)
Carle Pieters, Brown University, Providence, RI

Volatiles Regolith & Thermal Investigations Consortium for Exploration and Science (VORTICES)
Andy Rivkin, Johns Hopkins University/ Applied Physics Lab, Laurel, MD

CAN-2 TEAMS

Exploration Science Pathfinder Research for Enhancing Solar System Observations (ESPRESSO)
Alex Parker, Southwest Research Institute in Boulder, CO

Network for Exploration and Space Science (NESS)
Jack Burns, University of Colorado in Boulder, CO

Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS)
Thomas Orlando, Georgia Institute of Technology in Atlanta, GA

Toolbox for Research and Exploration (TREX)
Amanda Hendrix, Planetary Science Institute in Tucson, AZ

Center for Lunar and Asteroid Surface Science (CLASS)

Daniel Britt
University of Central Florida, Orlando, FL

1. CLASS Team Report

1.1 Daniel Britt: CLASS PI: UCF

Britt attended the Space Resources Roundtable, the Luxembourg Space Agency's Space Resources Week (where he gave two invited talks). This is part of the CLASS outreach to the NewSpace sector and includes educating resource companies on relevant space science and lunar/asteroid resource potential.

CLASS has established partnerships with 18 NewSpace commercial companies with the objective of making the best planetary science support available to this growing industry. CLASS services to this sector include the Exolith Lab, the CLASS Landing Team, and acting as a science team for NewSpace startups.

1.2 Adrienne Dove: Deputy PI: UCF

A. Dove and students continued analysis of the data returned from the Strata-1 experiment, worked with the Hermes experiments that were delivered to the ISS in Spring, 2019, and built and flew the Strata-S1 experiment aboard a Blue Origin suborbital flight in April, 2019. These experiments allow for the exploration of granular material behavior at low-gravity levels under vacuum conditions, with accelerations and perturbations similar to those that may be seen on asteroids and other small bodies (see example figure, next page, 3rd image). Additional experiments to explore landslides and regolith slope failure in variable gravity levels were flown on a ZERO-G parabolic research flight in November, 2019.

As part of the Planetary Landing Team, Dove has been working with Co-I Metzger to develop and test instrumentation for lunar lander flights. Some of this work will be tested with Masten Space Systems through NASA REDDI and SBIR funding. Also working with graduate student Wesley Chambers to explore plume-regolith interactions in a Drop Tower microgravity experiment.

> The CLASS Exolith Lab has become the defacto standard for planetary regolith simulants world-wide. The Lab has shipped 2418 Kg of simulants to 352 customers.

1.3 Christopher Bennett: Deputy PI: UCF

C. Bennett's work has focused on spectra of minerals, simulants, and meteorites using a number of techniques and wavelengths, including bidirectional diffuse reflection, hyperspectral Raman mapping, ToF-SIMS and HR-L2MS measurements. The Raman work produced maps of organic-mineral associations and demonstrated the ability to use Raman as a thermometer, but has also revealed potential sample modification resulting from Raman laser use. High-resolution tomographic imaging of meteorite samples can be used to visualize subsurface structures to interpret the processing history of the samples, as seen in Figure 1.

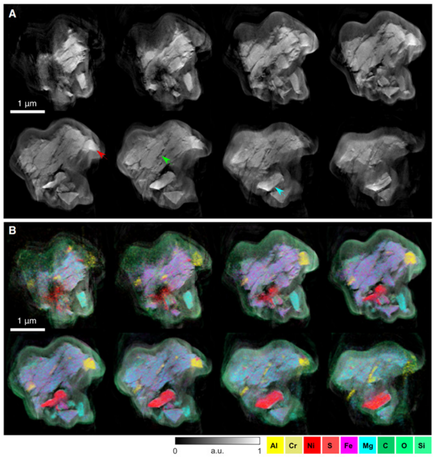


Fig. 1. High-resolution tomographic imaging of meteorite samples can be used to visualize subsurface structures to interpret the processing history of the samples, as seen here.

Additional measurements have surveyed different background standards over the visible, near-IR and mid-IR range, finding that this makes a huge difference in analysis and interpretation. These have lead to upcoming discussions with NASA's LRO team, as well as cross-team discussions with Amanda Hendrix and Melissa Lane (TREX) and Tim Glotch (RISE4).

1.4 Humberto Campins: Co-I: UCF

Observations with a number of ground-based telescopes have been used to complete the visible portion of a spectroscopic study of primitive inner belt families, including the Klio, Chaldaea, Chimaera, and Svea, families (Morate et al. 2019). These results have continued to show spectral diversity among inner-belt families, with at least three and possibly more distinct compositional groups: Erigone-like (hydrated and spectrally diverse), Polana-like (no 0.7-μm hydration feature and spectrally homogeneous) and Klio-like (similar to Erigone in the visible, Morate et al. 2019, and to Polana in the near-infrared, Arredondo et al. 2020). These results have implications for the surfaces of sample return targets Bennu and Ryugu.

1.5 Josh Colwell: Co-I: UCF

Multiple microgravity experiments on the behavior of asteroid regolith in response to exploration activities were flown in suborbital flights. The Collisions Into Dust Experiment (COLLIDE) flew on SpaceShipTwo (Virgin Galactic) in December, 2018 and February, 2019. While COLLIDE functioned properly, it was triggered prior to the microgravity phase so the video data show particle-particle interactions, but not an impact into a simulated regolith bed. The Collection of Regolith Experiment (CORE) flew on the New Shepard (Blue Origin) suborbital vehicle in December, 2019. This experiment simulates the retrieval of asteroid regolith via a simple scooping mechanism. It was a partially successful demonstration, collecting several particles of CLASS-developed regolith during its suborbital flight and demonstrating drastic motion due to the sampler impact (see figure 2).

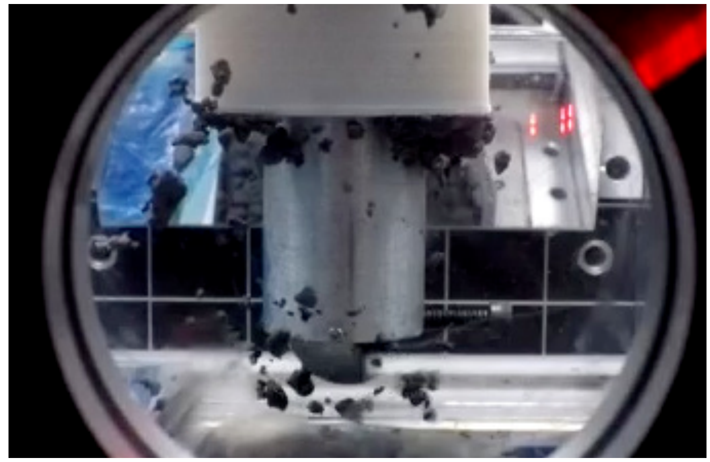


Fig.2. Image from the CORE experiment, which flew on the New Shepard (Blue Origin) suborbital flight. It was a partially successful demonstration, collecting several particles of CLASS-developed regolith during its suborbital flight and demonstrating drastic motion due to the sampler impact.

Ongoing experiments in the Center for Microgravity Research labs include experiments in the 0.75-second Drop Tower and cooled vacuum chambers. These experiments explore adhesion of small regolith particles to larger particles, simulating ejecta blocks and secondary impactors. Results show the dependence of the outcome of collisions between large particles and regolith on parameters such as velocity, regolith size distribution, and impactor surface properties.

1.6 Daniel Durda: Co-I: SwRI

D. Durda's work has focused on additional microgravity research experiments, with work underway to re-fly SwRI's Box-of-Rocks Experiment (BORE) on another Blue Origin suborbital spaceflight (flight funded through NASA SpaceTech-REDDI) to use the CLASS-developed CI regolith simulant and vacuum conditions. His team also flew several boxes of the same CI regolith simulant on a NASA Emerging Worlds-funded ZERO-G flight to examine the accretion/clumping behavior in microgravity (planetary accretion experiment). Shown in figure 3 is a frame grab from the video data showing rapid particle accretion in a box containing 10 grams of sieved 0.5-1.0mm CI simulant particles. The data gathered will also provide potentially useful information relevant to the Hermes ISS activities.

1.7 Yan Fernandez: Co-I: UCF

Work led by Fernandez's graduate student Mary Hinkle has used 25 epochs of near-IR spectra of NEA (433) Eros obtained at NASA/IRTF that simultaneously measure both the thermal emission of and the reflected sunlight from the regolith (figure 4). This unprecedented dataset is used to investigate the thermal and scattering properties of the regolith, with the determination that most of Eros's surface is consistent with a thermal inertia of 125 ± 25 J m-2K-1s-1/2 and a roughness crater fraction-equivalent of 35 ± 5%. However, several of our spectra require different thermal parameters, indicating that there is appreciable heterogeneity in Eros's regolith properties. These results are similar to those previously found for NEA (1627) Ivar. Future work on Eros will focus on investigating and characterizing these atypical locations on the body.

Ongoing collaboration with researchers at Arecibo to use IR spectra to interpret radar echoes and asteroid surface scattering properties, which are of significant importance for understanding asteroid surfaces in general, and especially the surfaces and structures of (potentially hazardous) Near Earth Objects.

Work is underway to adapt an N-body code to understand the behavior of ejecta that has been liberated from the surface of an asteroid. These results are being applied to a Scheila-like (main belt) asteroid, and to a DART-like scenario to inform mission design for that, and potentially other, impact/sampling missions.

1.8 Chris Herd: Co-I: University of Alberta

The active use of the cold curation facility continues – primarily for the development of curation methods for

Fig. 3. (Top) A frame from the BORE experiment (on a New Shepard suborbital flight) showing rapid particle accretion in a box containing 10 grams of sieved 0.5-1.0mm CI simulant particles.(Middle) Frame from Strata-S1 experiment aboard a Blue Origin suborbital flight in April, 2019. These experiments allow for the exploration of granular material behavior at low-gravity levels under vacuum conditions, with accelerations and perturbations similar to those thatmay be seen on asteroids and other small bodies. The suborbital flight provided conditions for technology development and testing. (Bottom) Effect of regolith cohesion on a sampling interaction (Scheeres and Sanchez, 2018, Prog. in Earth and Planetary Science).

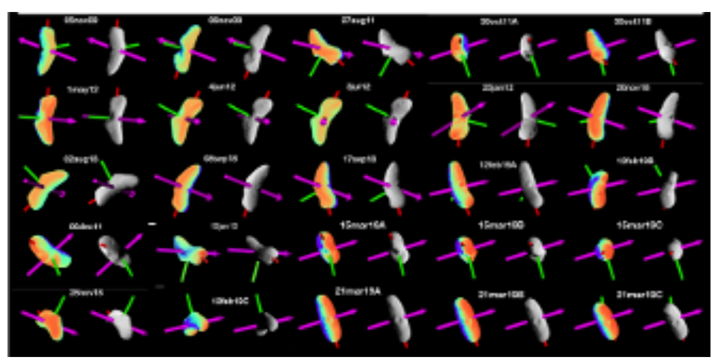


Fig. 4. Figure adapted from Hinkle et al. (2020, in review), showing plane-of-sky views of Eros at the mid-time of each of our 25 epochs of observation. Two images are shown for each observation: the rainbow image is a temperature map with red indicating the hottest temperaturesand purple the coldest, and the greyscale image shows the Sun's illumination in the optical regime. The magenta arrow is the rotation axis; the other two principal axes are the red and greenbars.

returned samples from objects such as asteroids, comets, and cold spots on the lunar surface; funded for the next 2 years by the Canadian Space Agency.

This year saw the establishment of an AllSky camera network in partnership with Curtin University (Australia), which searches for meteors and airbursts, and can be used to help locate meteorite falls with more rapid response.

1.9 Robert Macke: Co-I: Vatican Observatory

Measurements of thermal properties of chondrites and other meteorites. Thermal properties are necessary for understanding asteroid thermal behavior, which in turn affects asteroid dynamics and other phenomena. Heat capacity at low temperature (approx. 175 K) is measured by a technique of liquid nitrogen immersion, in which the specimen is rapidly cooled in liquid nitrogen and the mass of LN2 lost by this process indicates the total energy exchanged. This technique is coupled with work done by Cy Opeil (Boston College) to measure heat capacity as a function of temperature using a Quantum Design - Physical Properties Measurement System.

High-velocity Impact Studies. In collaboration with George Flynn (SUNY-Plattsburg), Melissa Strait (Alma College), and Dan Durda (Southwest Research Institute), we study the recoil parameter of high-velocity impacts on meteorites and meteorite analogs at the NASA Ames Vertical Gun Range. For this work, it is important to understand the relationship between the recoil parameter and the porosity. Porosity is measured at the Vatican Observatory meteorite laboratory using ideal gas pycnometry and 3D laser scanning.

1.10 Phil Metzger: Co-I: UCF/FSI

Leading the efforts of the CLASS Planetary Landing team, Metzger has been increasingly involved in analyses with various companies who have interests in lunar landings and plume-surface interactions (PSI). PSI's are becoming of increasing interest to NASA and other companies, as much of the physics of these interactions is poorly understood. This includes work funded through a SBIR with Masten Space Systems (also with A. Dove and students), a number of other private space companies, and in consultation with NASA centers. Metzger is also developing an instrument to fly on early lunar landers to better help constrain ejected dust size distributions and dynamics.

Modeling and predictions of lunar lander ejecta production and the resultant potential hazards to the other assets in the system have shown that significant amounts of lunar plume ejecta maybe be produced and even lofted to orbital altitudes. As previously seen with the Surveyor III mission, this can cause scouring, or worse, of other previously landed hardware on the surface. Modeling indicates that with the larger landers (i.e. the Lockheed Martin or Artemis landers) that have much higher thrust profiles, significant material may be lofted to great distances and orbital altitudes, potentially damaging orbital assets, as well. This points to a need for landing pads or other protection mechanisms, and also has significant geopolitical implications for how companies and international agencies will define landing zones on the lunar surface.

1.11 Robert Mueller: Co-I: NASA Kennedy Space Center, Swamp Works, Granular Mechanics & Regolith Operations (GMRO) Lab

Collaboration between Swamp Works and A. Dove (UCF) provided 2 experiment bays on a reduced gravity flight experiment (figure 5). The KSC /UCF team built small scale lunar excavator bucket drum segments that were filled with lunar regolith simulant. Cameras captured the flow of the regolith out of the drums in lunar and Martian gravity levels, rough vacuum, and at various rotational

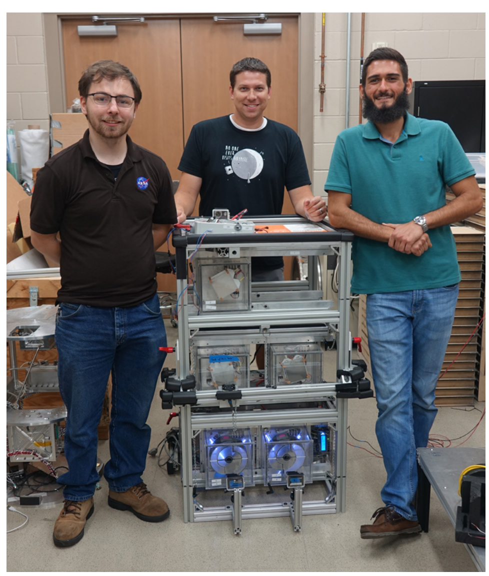


Fig. 5: Small-scale lunar excavator bucket drum experiments were developed for a reduced gravity flight with the UCF SLOPE experiments. A NASA KSC engineer and two NASA interns developed the experiment and built it. UCF provided flight data when they flew it on a reduced gravity flight.

speeds. This was a first step in proving the operation of a small bucket drum in lunar conditions. The tests showed that the bucket drum excavation concept is feasible in lunar gravity, which increases the technology readiness level (TRL) of NASA excavation concepts.

1.12. Cyril Opiel: Co-I: Boston College

We have gathered novel thermal inertia, thermal diffusivity, thermal expansion, and heat capacity measurements of a range of carbonaceous and metallic meteorites, as well as lunar samples, with samples at a range of 2-300K. These values can be used to improve models of the thermal behavior of meteorite parent bodies and are being used by the science teams of both the OSIRIS-REx and Hayabusa2 science teams.

1.13 Dan Scheeres: Co-I: University of Colorado

Developed detailed numerical models for asteroid regolith cohesion and incorporated them into simulations of natural asteroid environments and for sampling activities on asteroid surfaces. CLASS support has enabled Scheeres' team to be involved in aspects of the Hermes experiment, which will be a valuable dataset to compare with these numerical simulations.

Explored different mechanisms for creating large divots in certain classes of asteroids, such as 2008 EV5 and 2011 DP107. Specifically tested the role of cohesion in creating conditions for the loss of individual boulders or regions of greater strength on the equator.

1.14 Faith Vilas: Co-I: PSI

Continued research on the space weathering of primitive (dark) asteroids in the ultraviolet, resulting in multiple conference presentations and one paper in 2019. Additional research investigating evidence of hydration on the lunar surface has made significant progress and is ongoing.

1.15 Kevin Cannon: Collab: UCF

Developed a comprehensive geologic systems model for the development and evolution of icy regolith deposits at the lunar poles. This will help strategies related to prospecting for ice deposits, both for science campaigns and resource-based endeavors. The model includes an Ice Favorability Index, shown in figure 6, as a predictive model for where deep, substantial deposits of ice may have accumulated.

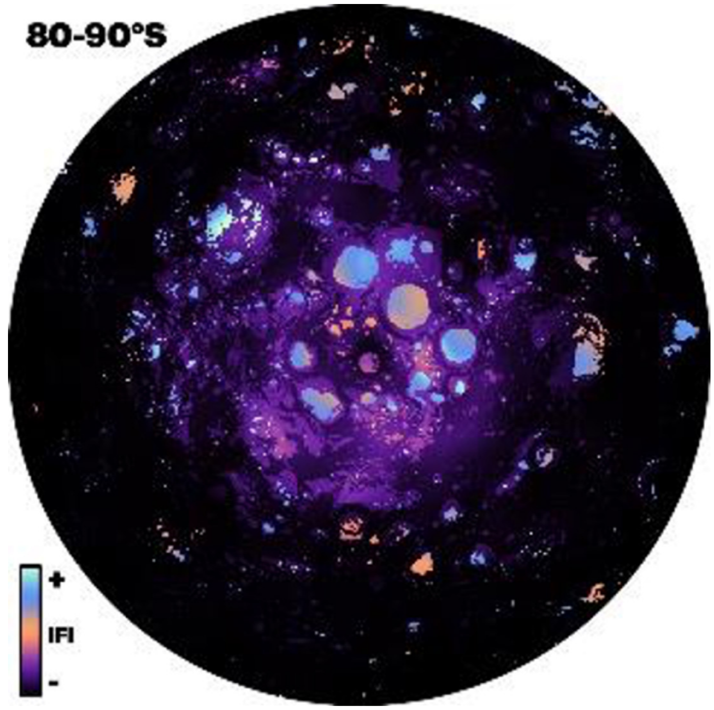


Fig. 6: A map of the Ice Favorability Index, which can be used as a predictive model forwhere deep, substantial deposits of ice may have accumulated.

2. Inter-team/International Collaborations

2.1. SSERVI Central and NASA

2.1.1 ESPRESSO (Parker)

D. Durda's BORE-II project is partnered with A. Parker's ESPRESSO SSERVI node at SwRI to adapt the magnetic grappling hardware recently flight-tested on a parabolic flight in October.

2.1.2 CLSE (Kring)

D. Britt worked with D. Kring of CLSE to develop the "Economic Geology of Lunar and Asteroid Resources" on-line graduate class.

D. Durda is working on Meteor Crater ejecta block mapping with D. Kring and team.

2.1.3 TREX (Hendrix)

F. Vilas is Deputy-PI for TREX and continues ongoing collaborations with A. Hendrix.

H. Campins worked on observations and interpretations of Asteroid (101955) Bennu with A. Hendrix

2.1.4 ISET (Bottke)

H. Campins worked with Bottke and K. Walsh using spectral and dynamical constraints to determine the likely main belt sources of spacecraft targeted Near-Earth Asteroids.

D. Scheeres worked with ISET to study the mechanics of cohesive asteroids and probe themes of motion on the surfaces of small bodies.

Bottke is a graduate advisory committee member of Britt's graduate student L. Pohl.

Britt spent two weeks during the summer working at SWRI Boulder on joint projects including the Lucy and New Horizons missions.

2.1.5 VORTICES (Rivken)

Y. Fernandez collaborated with R. Vervack (JHU/APL), E. Howell (U. Arizona), C. Magri (U. Maine) on NEA thermal properties.

2.1.6 REVEALS (Orlando)

C. Bennett, D. Britt, and graduate student L. Pohl collaborated with T. Orlando (Ga. Tech.) on thermo gravimetric analysis (TGA) of volatile-rich asteroidal regolith materials.

2.1.7 IMPACT (Horanyi)

D. Scheeres has coordinated research activities with IMPACT team members at the Colorado School of Mines.

2.1.8 FINESSE (Heldmann)

R. Mueller collaborated with M. Downs on aerial surveying using drones and remote sampling technologies using drone-mounted sampling systems.

2.2 International Collaborations

1. D. Britt established international collaborations with Cyril Opiel, Robert Macke, and Guy Consolmagno (Specula Vaticana), on meteorite thermal and physical property measurements.

2. Chris Herd is a member of the Global Fireball Observatory led by Phil Bland (Curtin U); actively working on establishment of the Western Canada arm of the Observatory.

3. Robert Macke collaborating with George Flynn (SUNY-Plattsburg), Melissa Strait (Alma College), and Dan Durda (Southwest Research Institute) on high-velocity impact studies.

4. H. Campins collaborating with Drs. S. Fornasier and A. Barucci (Paris), with Drs. P. Tanga and J. Hanus (Nice, France), and with Drs. J. Licandro and J. de Leon (Spain).

5. C. Bennett has collaborated with researchers at U. Lille (France) on hyperspectral Raman maps of meteorites and previously unidentified meteorite processing resulting from Raman and other laser techniques.

6. C. Runyon has had a number of international collaborations, especially for the 2019 South American Eclipse events and distribution of tactile books.

7. P. Abell works with the JAXA team on the Hayabusa2 mission, coordinating discussions for formal JAXA and Japanese membership into the International Asteroid Warning Network (IAWN) for NASA's Planetary Defense Coordination Office (PDCO). He is advising JAXA personnel on how the Martian Moons eXploration (MMX) mission has ties to Human SKGs and aids in the participation of NASA interests from both SMD and HEOMD perspectives.

3. Public Engagement

Cass Runyon leads the CLASS Public Engagement effort, but most of the CLASS Co-I's are also very active in their own endeavors. Below we describe some very successful EPO efforts, and highlight some of the Co-I involvement in public presentations and media.

3.1 Broad Education and Public Engagement efforts

3.1.1 Cass Runyon: Co-I: College of Charleston

- Creation and distribution of "Exploring the Moon: Apollo 50th Commemorative Edition" tactile book and online content; distributed across the country to participating libraries and schools.
- Development and writing for prototype book containing a family activity sheet, print, braille, and tactiles for learning about light pollution and effects

on astronomical observations.

- Coordinated group of high school students who are deaf to “sign” our book “Understanding Small Worlds in our Solar System.” This tactile book is available in print, audio and now a signed version; for use by students with a variety of disabilities.
- Creation and distribution of “Abre Tus Sentidos a los Eclipses: Sudamerica.” This tactile book highlights solar eclipses in general and the 2019 and 2020 eclipses in Chile and Argentina. Distribution occurred before the July 2019 eclipse; more will be distributed before the December 2020 eclipse with assistance from the US, Argentinian, and Chilean embassies.
- In addition, Runyon presented a number of Educator Workshops relating to the tactile books and other CLASS/SEEED-relevant science.
- Exploring the Moon: A Tactile Approach. Two-hour workshop for Virginia educators at Virginia Association of Education and Rehabilitation (AER) annual convention, Hampton, VA. 2/18/2019.
- The World Ender: A NASA Cross-Disciplinary PBL Unit. NSTA, St. Louis, MO, 4/14/2019
- Getting a Feel for Science: NASA Science Education Materials for Individuals Who Are Blind or Visually Impaired. Two-hour workshop at Penn-Del Association of Education and Rehabilitation (AER) annual convention, Hershey, PA. April, 2019.
- Making Space Science Accessible, Western Regional Space Grant Director’s Meeting, Big Sky, Montana, September 11 – 13, 2019.
- Innovative Differentiated Exploration Activities in Space Science (IDEAS), North Carolina Museum of Natural Science, Raleigh, NC, October 14 - 16, 2019.

3.1.2 Robinson Observatory

Y. Fernandez is the director of the UCF Robinson Observatory, through which UCF runs an extensive outreach program available to its 65,000+ students and residents of the greater Orlando area. Regular events are held throughout the semester, and two special events highlighted SSERVI-relevant science:

- “International Observe the Moon Night” on October 5 in which about 100 people came to watch the Moon and participate in moon-related and meteorite-related hands-on activities. Additional activities and talks were held at the UCF Library the week before the event.
- A special lunar eclipse viewing event on the night of January 20/21 in which over 200 people came to watch at least part of the total lunar eclipse.

3.1.3 Robotic Mining Competition

This competition is for university-level students to design and build a mining robot that can traverse challenging simulated lunar terrain. The mining robot must then excavate the regolith simulant and/or the ice simulant (gravel) and return the excavated mass for deposit into the collector bin to simulate an off-world, in situ resource mining mission. The complexities of the challenge include the abrasive characteristics of the regolith simulant, the weight and size limitations of the mining robot and the ability to tele-operate it from a remote Mission Control Center. Points from both the mandatory and optional categories are tallied for the grand prize, The Joe Kosmo Award for Excellence. NASA directly benefits from the competition by encouraging the development of innovative robotic excavation concepts from student teams which may result in clever ideas and solutions which could be applied to an actual excavation device and/or payload on an ISRU mission. In 2019 over 50 university teams from across the United States including Hawaii and Alaska competed in a remote competition. The competition had its 10th year anniversary in 2019 and will be held again in 2020.

3.1.4 Senior Design Classes

UCF/CLASS has sponsored a number of engineering senior design projects over the last few years. This year an Aerospace Engineering project was again sponsored by Swamp Works and CLASS by providing technical expertise to create a scaled, cheaper functioning engineering model of a NASA regolith excavation robot called Mini-Regolith Advanced Surface Systems Operations Robot (Mini-RASSOR). The students were responsible for writing control software and computer simulations for lunar regolith and water ice mining operations while the Mini-RASSOR mechanical engineering model was provided by NASA Swamp Works/CLASS. The project is in its second year and now has a robotic platform which can be 3D printed by the students for implementation of software and testing operations. The mechanical design that was developed with SSERVI support is being licensed to universities and educational institutions by the NASA KSC Tech Transfer office.

3.2. Public Presentations

Cyril Opiel Invited Talk: University of Connecticut, Storrs, CT. Topic: Condensed Matter from Space: Thermal and Physical Properties of CM2 Meteorites (November 19, 2019).

Chris Herd:

- Presentation to Edmonton Lapidary Club: "Meteorites and the University of Alberta Meteorite Collection" January 17, 2019; Invited.
- Alumni Educated Evening Presentation: "Unique Objects in the University of Alberta Meteorite Collection" February 14, 2019; Invited.
- Students for the Exploration and Development of Space (SEDS) Canada Presentation (Edmonton): "Space Exploration using Astromaterials" March 3, 2019; Invited.
- Friends of the University of Alberta Presentation: "Killer Asteroids: The Next Extinction Event?" May 14, 2019; Invited.

Robert Macke:

- Astronomy concepts and a night of stargazing, summer camp program at Santuario del Monte Lussari, Monte Lussari, Italy. September 28-29, 2019.
- Presentation: "Meteoriti ed Altro Materiale Extraterrestre" Associazione Arma Aeronautica, Caserta, Italy, 30 March 2019. (In Italian)
- Regular contributor to Sacred Space Astronomy blog (sponsored by the Vatican Observatory): 39 entries published in 2019.

Humberto Campins:

- Three lectures (one to NASA employees and two to the public) at the Kennedy Space Center on April 16, 2019.
- Presented lecture to the University of Central Florida's Astronomy Society on November 21, 2019.
- Cass Runyon: 50th Anniversary of Apollo Celebrations
- USS Yorktown – PBS and Apollo 8, Charleston, SC – exhibit and sharing of lunar education disks with the public throughout the year.
- SC ETV/WGBH Apollo Anniversary Celebration, Rock Hill Museum of Science, Rock Hill, SC, July 16, 2019.
- USS Yorktown -WGBH - Apollo 11 Celebration with veterans who helped to recover Apollo 8 capsule.
- Edinboro University Planetarium, Edinboro, Pennsylvania, Public shows highlighting the Apollo 50th Anniversary, Monday and Tuesday evenings from January 21 – April 29.

Paul Abell:

- Sacred Heart International School presentation on February 25, 2019 in Tokyo, Japan.
- Nishimachi Elementary School Visit on February 27, 2019 in Tokyo, Japan.
- Public Lecture supporting the Double Asteroid Redirection Test (DART) Mission on September 13, 2019 in Rome, Italy.
- Colloquium Presentation on NASA's Moon to Mars Initiative to the Instituto de Astrofisica de Canarias on October 10, 2019 in Tenerife, Spain.
- Planetary Defense Lecture to Girls and Technology, Norway on October 24, 2019 in Houston, Texas.

Josh Colwell and Addie Dove (with Jim Cooney) hosted the podcast "Walkabout the Galaxy." Exploration activities including CLASS research and NASA exploration missions and general science topics related to asteroids and the Moon are frequent topics. In 2019 there were over 42,000 downloads of 36 episodes.

Fig. 7: Former NASA Administrator Bolden explores a Touchable Moonrock display.

3.3. Media

Chris Herd has participated in a number of media interviews, including for NAIT (local college) radio on what evidence there is that the Apollo Moon landings were not faked (https://soundcloud.com/nr92-radio/the-feed-conspiracy-theories), with CBC TV in Calgary regarding plans to bring samples back from Mars (release of iMOST report), Friday, March 29th. Additional interviews related to the August 31, 2019 fireball over the Edmonton area and associated ground searching near Camrose, Alberta; including TV, radio, and newspaper between September 1st and 19th. A YouTube video created for the September 18th release generated over 8000 views in that timeframe.

Robert Macke has participated in a number of interviews, including on meteorites for Rai Radiotelevisione Italiana-TG3 Leonardo (Silvia Rosa-Brusin). August 7, 2019. Broadcast December 2019. (In Italian); on occasion of the 50th anniversary of the Apollo 11 mission. Texas Catholic Herald. (James Ramos), "Curator of meteorites 'finds God in all things,'" July 17, 2019, (circulated via Catholic News Service). Also did an interview on Jesuits in astronomy. America Magazine (William Critchley-Menor, S.J.) June 28, 2019 (email), "Why are so many craters on the moon named after Jesuits?," July 12, 2019.

Dan Durda has served as Science Consultant for Season 8 episodes of the Science Channel series "How The Universe Works" and was invited back for the next season of "Space's Deepest Secrets." In addition to appearing on camera in several of the planetary science episodes, he reviews and fact checks the scripts and rough cut edits of each episode, several of which have included lunar- and asteroid-related science and exploration themes related to our SSERVI research.

Humberto Campins was interviewed and quoted several times by US and international press outlets, including local WMFE (NPR) on December 10, and WKMG TV (CBS) on December 11 https://www.clickorlando.com/news/local/2019/12/12/nasas-asteroid-spacecraft-team-selects-site-for-sample-collection/

4. Student/Early Career Participation

Undergraduate Students

1. Matthew Bonidie, Boston College, Meteorite Physical Properties
2. Thomas Tartaglia, Boston College, Meteorite Physical Properties
3. Caroline Yaeger, Boston College, Meteorite Physical Properties
4. Miranda Holt, University of Alberta, characterization of Tagish Lake meteorite specimens
5. Roman Bukatiuk, University of Alberta (summer intern from Ukraine), sources of lab contamination
6. D. McCarty, UCF, asteroid observations
7. Jennifer Nolau, UCF, OSIRIS-Rex observations and interpretation
8. Riley Havel, UCF, spectral measurements and space weathering
9. Sarah Swiersz, UCF, spectral measurements and space weathering
10. Remington Cantelas, UCF, spectral measurements and space weathering
11. Anthony Meola, UCF Engineering, Microgravity and regolith research

12. Austin Rothermich, UCF Physics, Microgravity and regolith research
13. Claudia Orozco Vega, UCF Engineering, Microgravity and regolith research
14. Gillian Gomer, UCF Physics, Microgravity and regolith research
15. Jacob Anthony, UCF Engineering, Microgravity and regolith research
16. Jeb Massaro, UCF Engineering, Microgravity and regolith research
17. Madison Weinberg, UCF Engineering, Microgravity and regolith research
18. Melanie Robinson, UCF Physics, Microgravity and regolith research
19. Michael Wooley, UCF Engineering, Microgravity and regolith research
20. Raquel Guzman, UCF Engineering, Microgravity and regolith research
21. Richard Wakefield, UCF Engineering, Microgravity and regolith research
22. Richard Perdomo, UCF Engineering, Microgravity and regolith research
23. Trisha Joseph, UCF Physics, Microgravity and regolith research
24. Tyler Cox, UCF Engineering, Microgravity and regolith research
25. Yeniz Azconovieta, UCF Engineering, Microgravity and regolith research
26. Patrick Baranek, UCF Physics, Microgravity, plasma, and regolith research
27. Anna Metke, UCF Physics, Exolith Lab, rocket plumes
28. Christian Sipe, UCF Engineering, meteorite processes, UCF seminars
29. Makayla Peppin, UCF Physics, rocket plume interactions
30. Alexander Perruci, UCF Engineering, Exolith Lab, rocket plumes
31. Donovan Morrell, UCF Engineering, Exolith Lab
32. Cody Shultz, UCF Physics – started graduate school at Brown University

Graduate Students

33. Leos Pohl, PhD, UCF, physical properties of asteroids, weathering of NEO
34. Wesley Chambers, UCF, plume interactions and microgravity
35. Libby Tunney, MSc, University of Alberta, terrestrial contamination vectors in meteorites
36. Jarret Hamilton, MSc, University of Alberta, identifying source craters for the martian meteorites
37. Alex Sheen, PhD, University of Alberta, martian meteorite geochronology
38. A. Arredondo, PhD, UCF, asteroid family observations and characterization
39. V. Lowry, PhD, UCF, dynamical simulations of asteroid families
40. A. Malfavon, MSc, UCF, asteroid observations
41. Eric Markowitz, MSc, UCF, surface charging instrumentation and measurements
42. J. Rizos, PhD (Spain, working with UCF), asteroid observations and dynamics
43. Mary Hinkle, PhD, UCF, thermal modeling of asteroids
44. Jennifer Larson, PhD, UCF, dynamical modeling of ejecta clouds from asteroids
45. Amy LeBleu-DeBartola, PhD, UCF, characterization and mapping of meteorites
46. Brian Ferrari, PhD, UCF, spectral measurements and space weathering
47. Katie Salivicinska, PhD, spectral measurements and space weathering
48. Stephanie Jarmak, PhD, UCF, microgravity regolith experiments and numerical modeling
49. Keanna Jardine, PhD, UCF, regolith surface properties
50. Beverly Watson-Kemmerer, PhD (2019), Fl. Inst. Tech (supervised at GMRO, Mueller)

Postdoctoral Fellows

51. Patrick Hill, Postdoc, University of Alberta, advanced curation methods
52. V. Ali-Lagoa, Postdoc, Germany (working w/ Campins UCF)
53. J. Hanus, Postdoc, France (working w/ Campins UCF)

54. J. de León, Postdoc, Spain (working w/ Campins UCF)
55. C. Lantz, Postdoc, France (working w/ Campins UCF)
56. D. Morate, Postdoc, Brazil (working w/ Campins UCF)
57. M. de Pra, Postdoc, UCF
58. K. Cannon, Postdoc, UCF

5. Mission Involvement

1. New Horizons, Daniel Britt, Science Team Member
2. Lucy, Daniel Britt, Leader of the Interior and Bulk Properties Working Group, Science Team Member
3. CAESAR, Chris Herd, Science Team Member (Cold Curation Expert)
4. Mars 2020, Chris Herd, Returned Sample Science Participating Scientist
5. Lucy Mission, Robert Macke, Science Team, Collaborator
6. Psyche Mission, Dan Durda, Science Experiment Support
7. DART Mission, Dan Durda, Working Group 1: Modeling and Simulations of Impact Outcomes
8. DART Mission, Paul Abell, Working Group: Ground-based Observations, Surface Interactions and Proximity Science Working Groups
9. OSIRIS-REx, Humberto Campins, Imaging and Spectroscopy Science Team Member
10. OSIRIS-REx, Yan Fernandez, OCAMS Team collaborator
11. OSIRIS-REx, Paul Abell, Coordinator between OSIRIS-REx and Hayabusa2 Teams
12. NEOWISE, Yan Fernandez, Comet Group collaborator
13. NEO Surveyor, Yan Fernandex, Investigation Team Member, Co-I
14. Near-Earth Object Surveillance (formerly NEOCam) Mission, Paul Abell, science team member
15. European Space Agency's Gaia mission, Humberto Campins, Asteroid Spectroscopy, Collaborator
16. Lunar Reconnaissance Orbiter, Faith Vilas, Lyman Alpha Mapping Spectrometer, Participating Scientist
17. Hayabusa2, Faith Vilas, NIRS3 and ONC-T instruments Joint Science Team Member
18. Hayabusa2, Paul Abell, Multi-Scale Working Group, International Regolith Science Working Group, ONC Team Member, JAXA-NASA facilitator
19. JAXA MMX Mission, Rob Mueller, technical advisor Pneumatic Sampler
20. Lunar Lander Plume Effects, Rob Mueller/GMRO, Doppler Instrument development
21. SpaceX Starship, Rob Mueller/GMRO/CLASS, simulation and plume effects modeling, consultants
22. Artemis Lander, Gateway, Rob Mueller/CLASS, simulations of risk, consultants

6. Awards

Humberto Campins: NASA group achievement award to the entire OSIRIS-REx team, February, 2019.

Josh Colwell: named a Pegasus Professor by the University of Central Florida, the University's highest faculty honor, in April, 2019.

Faith Vilas: Fred Whipple Award and Lecture - 2019 – Planetary Sciences Section, American Geophysical Union.

Center for Lunar Science and Exploration (CLSE)

David Kring
Lunar and Planetary Institute, Houston, TX

1. CLSE Team Report

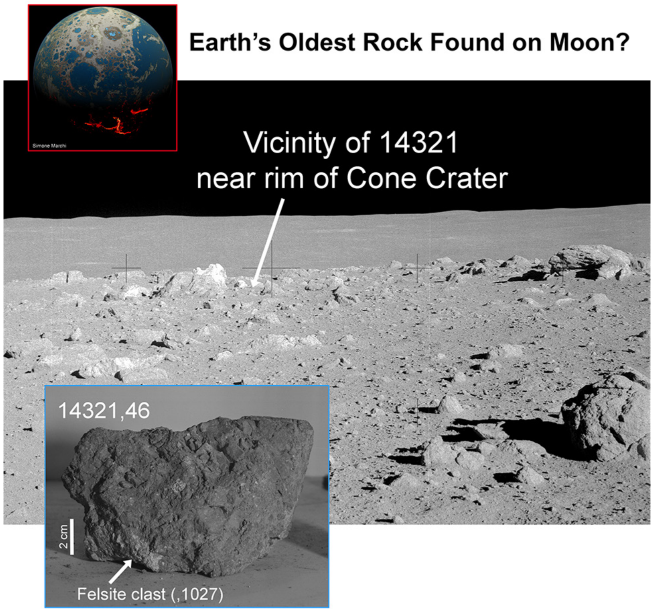
1.1 Science

1.1.1 Earth's Oldest Rock Found on the Moon?

The CLSE team and its international partners may have found the first piece of Earth on the Moon. Furthermore, if the sample is a piece of Earth, it is the first rock sample discovered from the Hadean eon of Earth history.

The CLSE team had previously developed techniques for locating impactor fragments in the lunar regolith (e.g., Joy et al., Science 2012) to evaluate the collisional evolution of the Moon and the dynamical processes that delivered asteroidal and cometary materials to the Moon. This year, the team harnessed that capability in a search for terrestrial meteorites (i.e., samples of Earth) that landed on the Moon. The result of that search (Bellucci et al., EPSL 2019) was a felsite rock fragment of zircon, quartz, and feldspar in an Apollo 14 breccia (see figure below).

The rock fragment crystallized in a terrestrial-like oxidized system, rather than in the reducing conditions characteristic of the Moon. Either the fragment is a Hadean piece of Earth or it crystallized in a completely new type of lunar magmatic system.



The team's analyses suggest the following scenario. The rock crystallized about 20 kilometers beneath Earth's surface 4.1 to 4.0 billion years ago. It was then excavated by one or more large impact events and launched into cis-lunar space. Previous work by the CLSE team showed that impacting asteroids at that time were producing craters thousands of kilometers in diameter on Earth, sufficiently large to bring material from those depths to the Earth's surface and launch it into space. Once the sample reached the lunar surface, it was affected by several other impact events, one of which partially melted the rock 3.9 billion years ago, and which probably buried the sample beneath the surface. The sample is, therefore, a relic of an intense period of bombardment that shaped the Earth-Moon system during the first billion years of Solar System history. After that period, the Moon was affected by smaller and less frequent impact events. The final impact event to affect the sample occurred about 26 million years ago, when an impacting asteroid hit the Moon, producing the small 340 meter-diameter Cone Crater, and excavated the sample back onto the lunar surface where astronauts collected it ~50 years ago (January 31–February 6, 1971).

1.1.2 Lunar South Pole Geology

We previously examined the geology of the Amundsen impact crater and Schrödinger impact basin within the south polar region. This year, we focused our attention on the south pole and impact craters in the immediate vicinity of the south pole. The studies included an assessment of

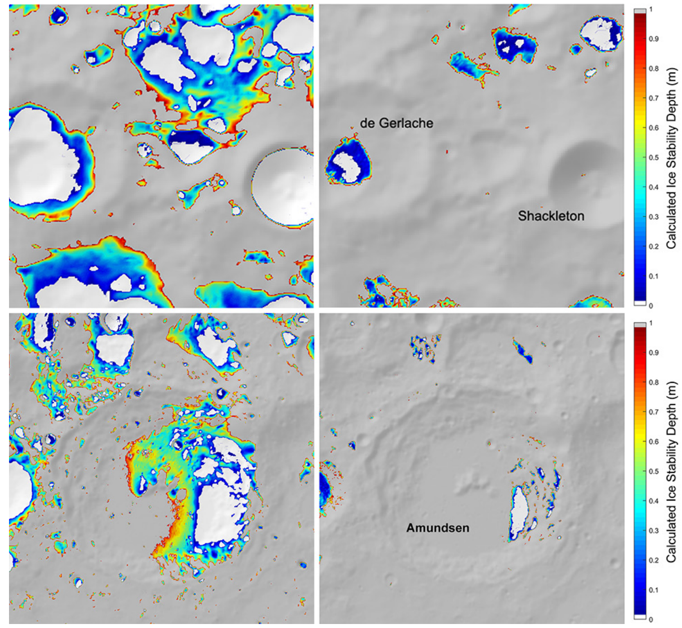
The lunar south pole is a heavily impact-cratered terrain, which affects lunar science objectives, the distribution of polar volatiles, and lunar surface operations.

EVA options for crew that might land in that area (Sections 1.2.1, 1.2.3, and 1.3.2).

The south pole occurs on the rim of Shackleton impact crater, in the vicinity of de Gerlache, Haworth, Shoemaker, Faustini, and several other impact craters. It is a heavily impact-cratered region. The nearest volcanic terrain is on the floor of the Schrödinger impact basin. Many of the craters host permanently shadowed regions (PSRs) that may have trapped volatiles, such as water, in the geologic past. Those issues have been the focus of other SSERVI-sponsored studies. This year we examined the ages of the craters, relative to the ages of volatiles sources, which affects the potential of trapping volatiles. While Haworth, de Gerlache, Shoemaker, and Faustini may be sufficiently old to capture volatiles delivered by impacting asteroids and comets during an early period of bombardment, Shackleton is too young. Likewise, Shackleton may not have been present to capture some of the volatiles vented by volcanic activity early in lunar history. Thus, Shackleton may be largely bereft of impact and volcanic volatiles and, instead, dominated by solar wind volatiles. We also initiated a series of calculations to determine the relative distributions of water ice and dry ice, assessed the consequences those distributions may have for meeting science and ISRU objectives, and included an estimate of the potential mass of ice within the uppermost meter of the lunar regolith. Examples of those products are maps (see figure) of the calculated stability of water ice (left) and dry ice (right) in the upper 1 meter of regolith in Shackleton (top) and Amundsen (bottom) craters.

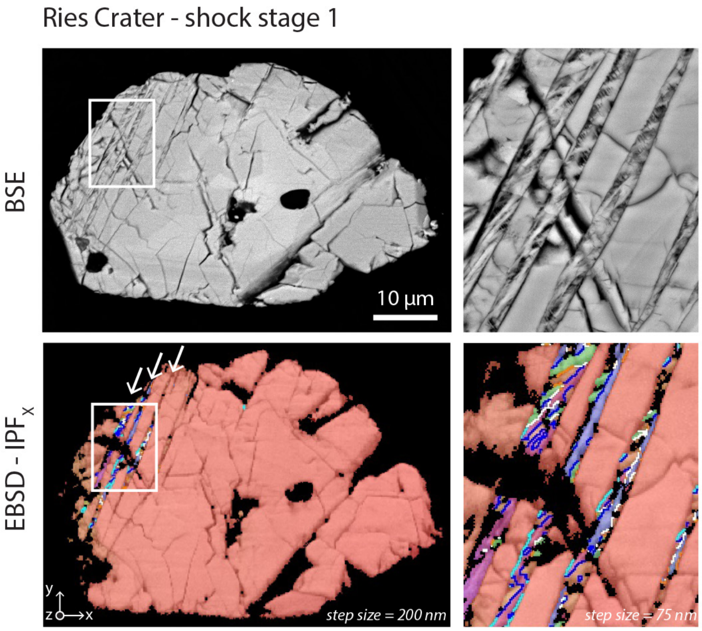
1.1.3 Shock-deformation of Age-defining Minerals

The timing of impact events, particularly those early in lunar history, is an important parameter for assessing the accretion and dynamical evolution of the Solar System.



As noted above, it is also an important parameter for assessing the delivery of volatiles to the lunar surface and the potential trapping of them in polar PSRs. CLSE addressed that issue is two ways this year. First, in a study of impact melt clasts extracted from an Apollo 16 sample (Niihara et al., MAPS 2019), we showed they were produced by four distinct impact events within a small interval of time (4000 ± 23 and 3832 ± 75 Ma), indicating they were not produced by a single impact event, such as the Imbrium basin-forming event. Rather, the data support the lunar cataclysm hypothesis, suggesting there was an unusually large number of impact events at the end of the basin-forming epoch.

That study used the Ar-Ar radiometric system, which is a classic system in Apollo sample science. In recent years, the team has also been helping the planetary science community develop new techniques that use the U-Pb radiometric system. Before the method can be applied routinely and confidently, we need to understand how impact-generated shock events affect the radiometric system. For that reason, this year we studied several mineral carriers of U-Pb that were collected at terrestrial analogue impact craters where the geologic context of each sample, within a crater, is known. That generated a series of papers that investigated apatite (Kenny et al., Geology 2019), zircon (Schmieder et al., MAPS 2019), and the production of a new high-pressure mineral (Erickson et al., Geology 2019) (see figure above). These



types of analogue studies are important because (a) their context greatly enhances our ability to interpret lunar samples that are often displaced from their original geologic context and (b) they allow us to refine analytical techniques on samples that are volumetrically abundant relative to lunar samples.

1.2 Exploration

We investigated several issues needing attention prior to a 2024 landing of crew at the lunar south pole, plus several other issues needed to develop a sustainable deep space exploration program.

1.2.1 Fast-track Studies for Artemis

Following the Vice President's March 26 directive to land astronauts at the lunar south pole within five years, CLSE initiated several fast-track studies to help the agency meet that mission objective. Initial results were delivered to NASA within a month, presented to the community at subsequent conferences, and are being prepared for journal publications. The status of each study follows.

CLSE initiated a study of boulders and boulder tracks around the south pole to identify targets for science sampling and to evaluate trafficability conditions that affect crew and rover traverses. Preliminary results were presented at the NASA Exploration Science Forum (NESF) [Bickel and Kring, 2019] and a full-length paper has been submitted for publication.

> Throughout the year, the CLSE team provided south pole data to NASA engineers working on lunar landers, EVA systems, and mobility systems, as part of an effort to land astronauts at the south pole within five years.

CLSE initiated a study of the geology of the south pole to identify an integrated set of science and exploration targets, building on the team's recently published (Allender et al., Adv. Space Res. 2019) study of a landing site and two traverses at the south pole that addressed both science and ISRU objectives. PI Kring took the lead on that focused assessment (Kring, NESF 2019a), but was then joined by the team's Exploration Science interns (Section 2.3.2). That work produced a paper about the formation of Shackleton crater (Halim et al., submitted) and a manuscript that describes two types of terrains in the immediate vicinity of the south pole (Gawronska et al., in preparation). Preliminary results will be presented at the spring 2020 Lunar and Planetary Science Conference (Halim et al., 2020; Harish et al., 2020; Gilmour et al., 2020).

CLSE created a plan to develop and implement lunar surface science operations for an initial 2024 landing and subsequent surface missions that are part of a sustained exploration program. PI Kring briefed that plan to NASA Headquarters and presented a version of it to the lunar community at the NESF (Kring, NESF 2019b).

CLSE began a project with CLASS to evaluate cargo and crew lander dust-pluming effects to determine the distance and/or local south pole topography needed to protect previously deployed surface assets. Preliminary results were presented by a CLASS colleague (Metzger et al., 2019) at the NESF.

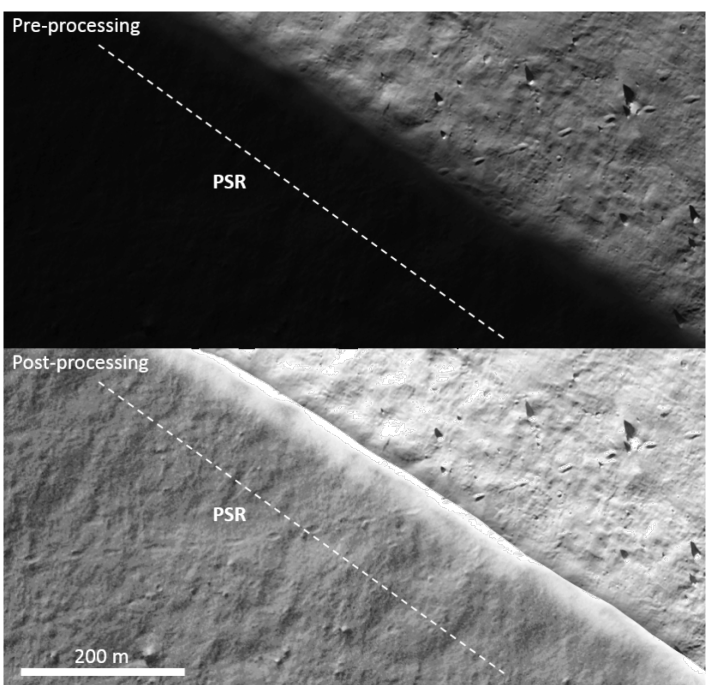
CLSE also responded to two requests from NASA Headquarters and SSERVI Central, providing input for a science reference mission to the lunar south pole (Kring et al., 2019a) and identifying methods that can address strategic knowledge gaps associated with science support of human missions (Kring et al. 2019b).

1.2.2 Trafficability in ISRU-relevant Terrains

To support efforts to explore ISRU-related sites needed for a sustainable exploration program, CLSE has been evaluating the trafficability of those areas. Our first report (Bickel et al., JGR Planets 2019) examined pyroclastic deposits where water might be produced by hydrogen reduction. A second report (Sargeant et al., JGR Planets, in press) examined trafficability in permanently shadowed regions (PSRs). By enhancing the signal produced by scant photons reflected from PSRs, we showed that boulder tracks continue, without apparent change, from sunlit areas into PSRs (see figure below). That suggests the bearing capacity is similar and that trafficability will also be similar. CLSE also continued its contribution to a NESS-led study of tele-operation of surface assets.

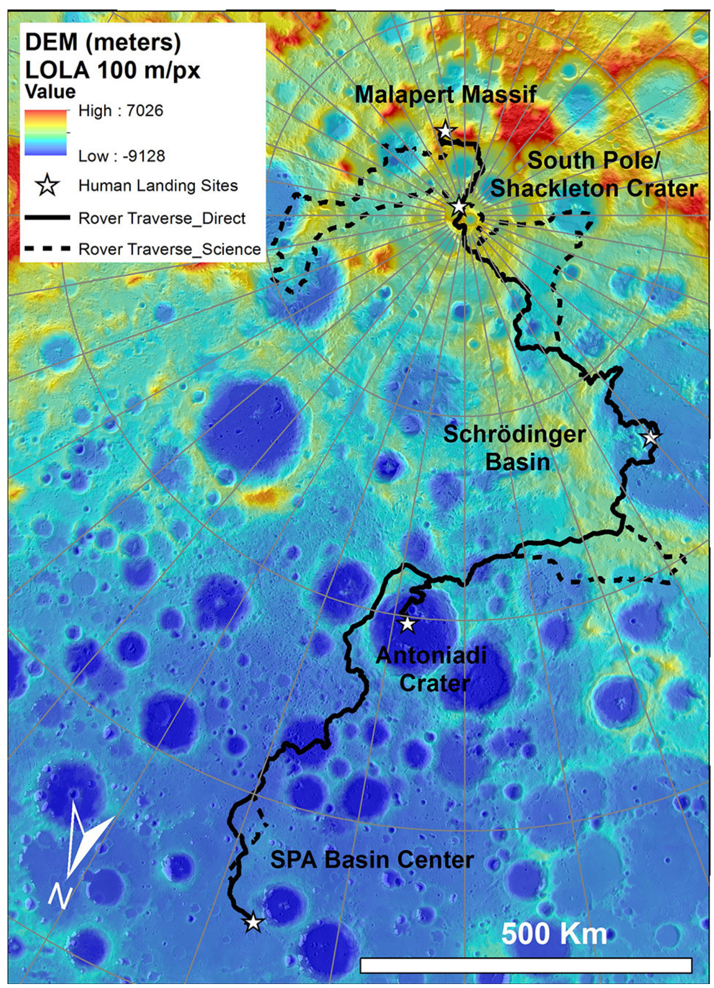
1.2.3 ISECG Design Reference Mission

We were asked by NASA HEOMD to evaluate landing site and traverse options at five locations in the south polar region that are part of the International Space Exploration Coordination Group (ISECG) design reference mission (DRM) for humans on the lunar surface. We were also asked if trafficable conditions existed between those landing sites, so that mobile assets can be tele-robotically redeployed to the next landing site. The study evaluated topography, slope conditions, and communication coverage from an orbiting asset. The results of that study (Allender et al., Adv. Space Research 2019) were released this year. Two 14-day-long traverses were identified around each of five landing sites (Malapert massif, Shackleton impact crater/south pole, Schrödinger impact basin, Antoniadi impact crater, and the center of the South Pole-Aitken impact basin). Tele-robotic traverses between the landing sites appear largely feasible (see figure below), although two locations along the routes were identified for further study. The science objectives to be met were documented. Furthermore, it was shown that ISRU-related surveys were possible between crew landings during the tele-robotic phase of the DRM. The study indicates the DRM concept is sound and suggests more detailed studies are warranted.



1.2.4 Lunar South Pole Maps

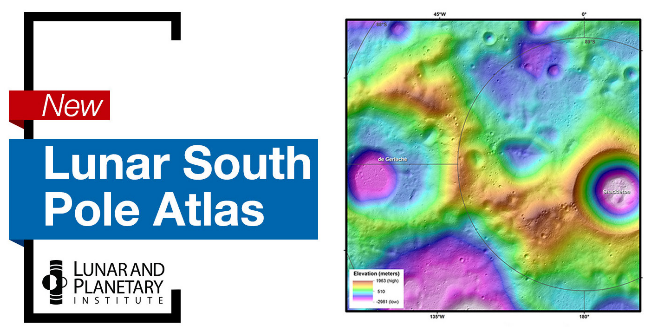
CLSE collaborated with the Regional Planetary Image Facility at the Lunar and Planetary Institute (LPI) to generate an on-line *Lunar South Pole Atlas* (see figure).



We produced several new map products designed specifically to assist polar exploration. We also produced new illustrations that explain several unique features of the lunar south pole. Those new products were integrated with existing maps and illustrations to provide a comprehensive resource for the Artemis community.

1.2.5 Resource Tonnage of Polar Water Ice

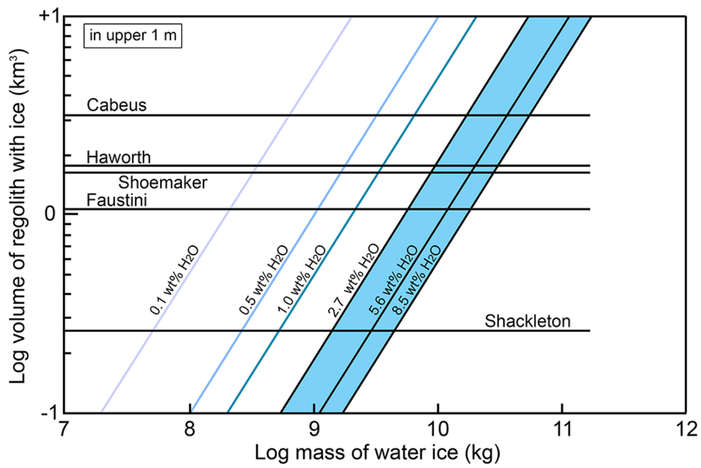
Near-surface ice deposits that do not require energy for the removal of overburden may be attractive ISRU targets. Using the calculated water ice distributions (Section 1.1.2), the potential resource tonnage was calculated in the upper 1 meter (see figure). Resource tonnage is derived assuming 5.6 ± 2.9 wt% H_2O in the regolith, as determined from the LCROSS experiment. Because that experiment targeted Cabeus crater, the resource tonnage calculated for Cabeus should be viewed with a



www.lpi.usra.edu/lunar/lunar-south-pole-atlas/

higher confidence than that for other sites (e.g., Haworth, Shoemaker, Faustini, and Shackleton crates). We note that the 5.6 wt% value is strictly applicable only to the coldest portion of Cabeus, where dry ice is stable at the surface. Thus, we also calculated the potential resource tonnage for lower proportions (0.1, 0.5, and 1.0 wt%) of H_2O in the regolith (see figure).

Model calculations suggest 2 × 10^{10} kg to no more than 5 × 10^{10} kg water ice could be recovered from the uppermost 1 m of regolith in Cabeus crater. Similar values for Haworth, Shoemaker, Faustini, and Shackleton are 9 × 10^{9} to 3 × 10^{10} kg, 9 × 10^{9} to 3 × 10^{10} kg, 6 × 10^{9} to 2 × 10^{10} kg, and 1 × 10^{9} to 4 × 10^{9} kg, respectively. For the coldest regions of the PSRs, where dry ice is stable at the surface, the potential resource tonnage of other ices (OH, CH_4, CH_3OH, CO_2, C_2H_4, SO_2, NH_3, and H_2S) was also calculated and is available (Kring et al., LPSC 2020). Additional tonnage



can be recovered at deeper (>1 m) horizons. Depending on the resource recovery methodology, it may be more efficient to access deeper ice at a single location than surface ice at geographically distant sites. In either case, it will be important to evaluate sublimation rates of subsurface ices as overlying regolith is removed.

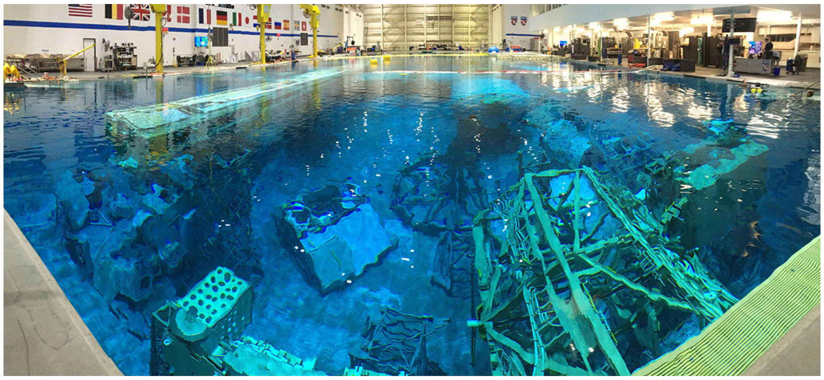
1.3 Training

Our science and exploration programs are integrated with several training programs for young investigators. This year, we hosted the fourth edition of the Exploration Science summer intern program. The program introduces graduate students to several bridging activities between science and exploration. The program also has an important research component. Because the program began soon after the March 26 directive to land astronauts at the lunar south pole, the students focused their efforts on that target.

1.3.1 Providing the Tools for Conducting Lunar Exploration

Students were taught methods for lunar surface sample collection, lunar sample curation, and the potential outcomes of lunar sample analyses. As part of that training, students were given access to the Apollo sample curation facility at JSC (see figures) to gain a first-hand understanding of lunar sample properties while learning sample curation techniques and optimized sample documentation methods to ensure continuity in sample analyses between laboratories and across decades of time.

Because the students are studying lunar surface sites suitable for EVA during the initial phases of Artemis (Section 1.3.2), when surface operations may be coordinated with an orbiting Gateway, it is important for them to better



understand the basics of EVA and training for EVA. With that objective in mind, students were given an opportunity to study an EVA at the Neutral Buoyancy Laboratory (see figures above). Lessons learned include suit assembly and function, airlock activities, the importance of communication between crew and supporting staff, and patterns of movement in low-g environments.

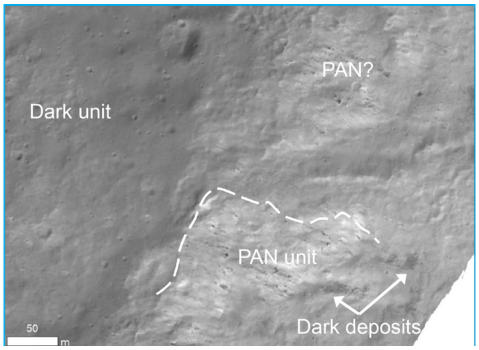
It is also necessary to provide students adequate context about lunar landings and the types of terrains involved in them. To initiate that discussion, students were introduced to a Lunar Landing Research Vehicle (LLRV) used during Apollo for training astronauts to land using the Lunar Module (LM). The vehicle provided a good backdrop for a discussion of lunar surface obstacles (craters, boulders, and dust), how those obstacles may affect a landing, and how, in turn, a vehicle descent may affect samples in the vicinity of a landing site. That element of their training was then augmented with the principles of EVA traverse planning in an outdoor facility at JSC. While standing on the rim of a simulated impact crater, the students were taught some of the challenges of navigating that type of topography in a spacesuit and rover, and the types of sampling strategies one might employ in that type of terrain.

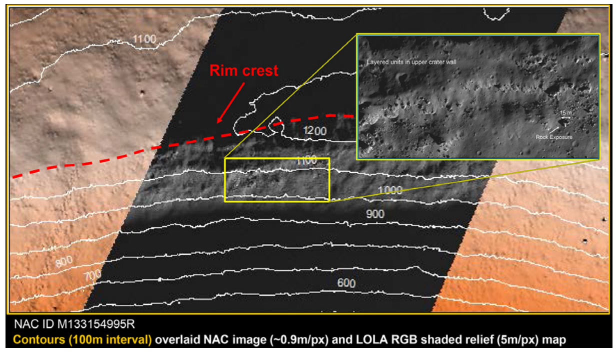
1.3.2 South Pole – Shackleton Crater Geology

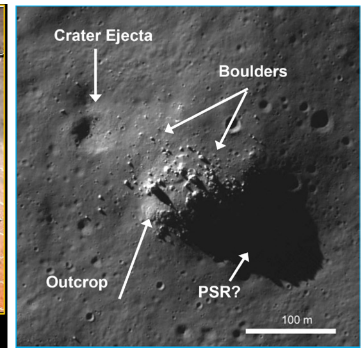
The Exploration Science interns' study of the south pole and Shackleton crater revealed the crater was excavated from two types of terrains: a crystalline terrain that includes masses of pure anorthosite that are probably remnants of the Moon's original crust; and a layered terrain that is stratigraphically above the anorthosite and probably represents layers of impact ejecta from nearby craters. We evaluated potential EVA options from the lunar south pole and identified several targets of interest (e.g., see figures next page): boulders and immense exposures of ejected rock far larger than anything encountered during Apollo, that have the potential for illuminating how parts of the lunar crust are constructed; a second, more mafic rock lithology whose provenance remains mysterious, and a series of small PSRs suitable for an initial investigation of volatile substances near the south pole. The students also used a shock physics code to model the formation of Shackleton crater and showed it could be produced by a 1.5 kilometer diameter asteroid hitting the lunar surface at 15 kilometers per second.

2. Inter-team/International Collaborations

An essential ingredient in the success of SSERVI and the CLSE team's work is the rich collaborations that we have developed with other teams within SSERVI and its international partners. However, as SSERVI CAN 1 activities were winding down, so, too, did many of those







collaborations. The few collaborative activities that we were able to maintain between CAN 1 and CAN 3 contracts are described here.

2.1 Inter-team Collaborations

CLSE continued to work with SSERVI colleagues on the VOLATILES team at Goddard Space Flight Center. In particular, we examined the transport and sequestration of volatiles in the polar regions. Whereas we had previously focused our attention on volatiles emitted by the Schrödinger volcanic vent (in a study led by CLSE PI Kring), this year CLSE supported a project led by VOLATILES Dana Hurley, which was a detailed analysis of carbon transport and deposition in polar regions. Preliminary results were presented at the fall meeting of the American Geophysical Union.

CLSE assisted the CLASS team at the University of Central Florida with the development of an ISRU-relevant course. The class will be implemented in the spring semester of 2020.

2.2 International Collaborations

One of this year's most exciting research results (Section 1.1.1) is a grand example of how international collaborations enrich our work. This study was prompted by CLSE team PI David Kring, but the implementation was led by two of our international partners, Jeremy Bellucci and Alex Nemchin, of the Swedish Museum of Natural History and Australia's Curtin University. The project also involved collaborators from the United Kingdom's Imperial College London, The Netherland's Vrije Universiteit Amsterdam, and the Australian National University.

Our analyses of minerals used to determine the collisional evolution of the lunar surface (Section 2.1.3) involved international partners in Australia, Japan, and Sweden.

Our Exploration Science summer intern program draws upon international talent and, in 2019, involved participants from Canada, India, and the United Kingdom.

Carolyn H. van der Bogert of Germany's *Westfälische Wilhelms-Universität Münster also contributed to a study of polar volatiles. A manuscript with those results is in preparation; more details about that project should be available in next year's annual report.*

3. Public Engagement

In 2019 CLSE continued to engage public audiences through traveling library exhibits and public programs. Education Lead Shaner continues to participate in the International Observe the Moon Night Coordinating Committee. A partnership with a Houston-based quintet, WindSync, continues to flourish, collaborating on multiple STEAM events. This year that collaboration included the premier of a new piece of music, *Apollo* by Marc Mellits, commissioned specifically for the Apollo 11 50th anniversary. CLSE also purchased two lunar meteorite touch samples with displays through SSERVI Central.

3.1 Traveling Library Exhibits

CLSE's stock of traveling library exhibits were a highly sought after resource in 2019. Composed of three conference-style pop-up banners, each exhibit interprets

a topic of lunar or asteroid science and exploration using vivid imagery and text. Libraries across the U.S. participated in a national summer reading program titled "A Universe of Stories" which emphasized space science topics, particularly the Apollo 11 50th anniversary. As of November 6, traveling library exhibits were loaned to 30 institutions and viewed by over 130,000 members of the public. Since the beginning of the exhibit program, exhibits have been viewed by over 500,000 people nationwide (see map below).

3.2 Public Programs

In addition to International Observe the Moon Night, CLSE participated in numerous public events highlighting lunar science and exploration.

- **Mar 10** PI Kring presentation at a *WindSync* performance
- **Jun 22** PI Kring "Gravity Assist" podcast with Dr. Jim Green
- **Jul 20** LPI Apollo 11 50th anniversary event
- **Jul 20** PI Kring presentation at Houston Museum of Natural Science with another *WindSync* performance (see figure)
- **Sep 11** CLSE team member Fagan hosts "Fireside Chat" with Apollo 16 astronaut Charlie Duke at Western Carolina U.
- **Sep 20** CLSE info table and lunar meteorite touch sample at *WindSync* performance in downtown Houston
- **Oct 5** International Observe the Moon Night event at LPI (see figure above)
- **Oct 11** PI Kring presentation for JSC Astronomy Club
- **Oct 19** PI Kring seminar with Rice U. space studies graduate students
- **Oct 29** Shaner hosts virtual panel discussion at the 2019 LEAG meeting with CLSE team member Needham

3.2.1 Public Programs Impact

CLSE participation in public programs reached 1700 people in 2019, conservatively. This includes over 200 views of the recording of the LEAG virtual panel to date. This recording is available at https://youtu.be/MIQJgVYZFCQ.

4. Student/Early Career Participation

The prime cooperative agreement ended early in the year. Projects were generally completed prior to the end of that agreement and only in a few cases were allowed to continue during a no cost extension. For that reason, the number of participants is greatly reduced this year compared with that in previous years.

Graduate Students – Laboratory Researchers

1. David Burney *(University of Notre Dame)*
2. Graduate Students – Exploration Science Summer Intern Program
3. Venkata Satya Kumar Animireddi *(Andhra University, India)*
4. Natasha Barrett *(University of Alberta, Canada)*
5. Sarah Boazman *(University College London, UK)*
6. Aleksandra Gawronska *(Miami University, USA)*
7. Cosette Gilmour *(York University, Canada)*
8. Samuel Halim *(University of London, UK)*
9. Harish *(Physical Research Laboratory, India)*
10. Kathryn McCanaan *(University of Manchester, UK)*
11. Jahnavi Shah *(University of Western Ontario, Canada)*

Postdoctoral Researchers

1. Dr. Jeremy Bellucci *(Swedish Museum of Natural History)*
2. Dr. Katherine Bermingham *(University of Maryland);*

recently hired to be an Assistant Professor at Rutgers University

3. Dr. Katharine Robinson *(USRA-LPI)*
4. Dr. Martin Schmieder *(USRA-LPI)*; recently hired by the Neu-Ulm University, Germany
5. Dr. Joshua Snape *(Swedish Museum of Natural History)*

New Collaborating Team Members

1. Dr. Jeremy W. Boyce *(Johnson Space Center)*
2. Dr. Gary R. Huss *(University of Hawaii)*
3. Dr. Kazuhide Nagashima *(University of Hawaii)*
4. *Dr. Matthew A. Siegler (Planetary Science Institute)*
5. *Dr. Julie D. Stopar (USRA-LPI)*

Promoted Team Members

1. Dr. Debra Needham (Marshall Space Flight Center); recently promoted to the CLSE's Deputy Team Leader
2. See also items (2) and (4) in the section "Postdoctoral Researchers" above

5. Mission Involvement

1. Lunar Reconnaissance Orbiter, Dr. Julie Stopar, Lunar Reconnaissance Orbiter Camera, Science & Operations
2. Lunar Reconnaissance Orbiter, Professor Dr. Harry Hiesinger, Lunar Reconnaissance Orbiter Camera, Science (International Partner)
3. Lunar Reconnaissance Orbiter, Dr. Carolyn van der Bogert, Lunar Reconnaissance Orbiter Camera, Science (International Partner)
4. The CLSE team has informally provided information about polar conditions to the VIPER development team

6. Awards

- Dr. Debra H. Needham received SSERVI's Susan Mahan Niebur Award for early career contributions to exploration science
- Dr. Wendell Mendell received SSERVI's Michael Wargo Award for significant contributions to the integration of exploration and planetary science
- Prof. Richard J. Walker received AGU's Harry H. Hess Medal in recognition of outstanding achievements in research on the constitution and evolution of the Earth and other planets

Dynamic Response of Environments at Asteroids, the Moon, and Moons of Mars (DREAM2)

William Farrell
NASA Goddard Space Flight Center, Greenbelt, MD

1. DREAM2 Team Report

DREAM2 has 4 space environmental themes that are discussed below: space plasma interactions at airless bodies (1.1), collisionless atmospheres or exospheres formed at airless bodies (1.2), radiation environment (1.3), and surface interactions (1.4). We also describe DREAM2's direct application of our science to exploration endeavors (1.5) and DREAM2's footprint into space science and exploration mission activities (5.0).

1.1 Plasma Environment

The DREAM2 plasma team continued its successful campaign to understand the impact of the space environment on airless body surfaces and exospheres of all scales. Airless bodies likely represent the most common type of object in our Solar System and beyond, and they interact directly with the space environment, which consists in large part of plasma. By most estimates, more than 99% of the visible matter in the universe is ionized and therefore classified as plasma. The plasma-surface and plasma-exosphere interactions that the DREAM2 plasma team investigates are therefore of fundamental importance in our universe, with implications for airless bodies of all sizes both within and outside of our Solar System.

The DREAM2 plasma team conducted fundamental data analysis and theoretical investigations focused on the Earth's Moon and other small bodies. Data analysis highlights include detailed statistical studies of the interaction between the solar wind and small-scale lunar crustal magnetic fields (Howard et al., 2019), case studies of the interaction of the Moon and its exosphere and ionosphere with the ambient environment of the terrestrial magnetotail lobes (Cao et al., 2019), and statistical studies of the electric potential structure of the lunar wake and its dependence on the solar wind conditions (Xu et al., 2019). Theoretical work focused on the unique plasma physics of the solar wind flowing past small-scale lunar craters (Rhodes and Farrell, 2019), with significant implications for the craters in the lunar polar regions. This study was the basis for examining the tribocharging effect from drill operations: due to the reduced plasma influx into polar craters, drilling could lead to anomalous charging (see Section 1.4).

Another exciting DREAM2 plasma highlight was a very recent statistical study of the ion populations that impact Phobos, and the implications of this ion bombardment for sputtering of material from the surface this Martian moon (Nénon et al., 2019). This study came to the conclusion that bombardment of the surface by heavy ions of planetary origin is more important than bombardment by the light solar wind ions when Phobos passes through the region downstream of Mars (The Martian magnetotail, see **Figure 1**).

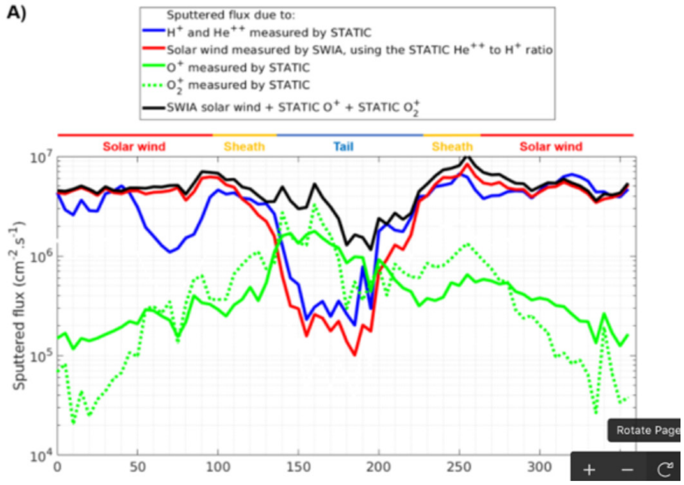


Figure 1. Predicted sputtered flux from Phobos by solar wind (blue, red) and planetary (green) ions.

1.2 Exospheres at Airless Bodies

Exospheres, or collisionless atmospheres, form as a direct result of space weathering of the surfaces at airless bodies. Solar radiation, space plasmas, and meteor impacts all create outgassing in the form of thermal, photonic, and electron desorption, plasma sputtering and impact vaporization. Depending upon the species released, the ejection velocity, and the gravity of the body, the material can remain in the local space environment to form a surface bounded exosphere. DREAM2 team members continue to contribute to knowledge of the lunar volatile and exosphere environment from observations, Monte Carlo models, and laboratory studies.

By examining the residual amounts of sodium and calcium in the lunar soil, Rosemary Killen and Prabal Saxena found that the Sun had to have been a slow rotator during the early formation period of the Solar System (Saxena et al., 2019). They argued that a fast-rotating sun would have had a larger number of coronal mass ejections that would have sputtered away the near-surface volatiles sodium and potassium. However, a slower rotating sun had fewer CME events over time, leading to greater retention of the species. A key input in this study was Killen's paper from 2012 that examined the greatly increased sputtering rate of sodium and potassium during solar storms – a study that was part of DREAM's 2011 Solar Storm/Lunar Atmosphere Modeling (SSLAM) effort. This is a case where past DREAM efforts have stimulated and enable today's very topical research.

At the 2019 NASA Exploration Science Forum, Parvathy Prem presented the modeling study of the exospheric response to the release of spacecraft exhaust volatiles. The simulation merged the collisional aspects of the gas near the nozzle and the surface, and the collsionless character further away from the plume and surface. These modeling efforts are now being integrated into the CLPS lander payloads, given that three mass spectrometers are to fly to the lunar surface on the Astrobotic lander in the 2021-2022 timeframe. According to the Prem studies, these mass spectrometers will sense surface emissions from gases deposited by the landing exhaust.

Killen et al. (2019) examined the archived ALSEP/Lunar Atmosphere Composition Experiment data specifically focusing on the response of the noble gas Neon to driving solar events. Neon is a species found in the solar wind that implants and is re-emitted from the surface to form an exosphere. Neon is lost via photoionization, with an ionization lifetime of 300 days. Killen's team found that the low Neon densities were not consistent with simple source-loss models, concluding that some other yet-to-be-identified loss process had to be involved.

Besides the LACE study, Rosemary Killen continued to observe the lunar sodium exosphere via a remotely controlled telescope located at the Winer Observatory in Sonoita, Arizona. The telescopes are controlled at a dedicated workstation at Goddard SFC. A large systematic baseline of lunar exospheric sodium observations has now been obtained and can be compared with other data sets like that associated with space weather. The data set is unique: other ground-based observatories have to

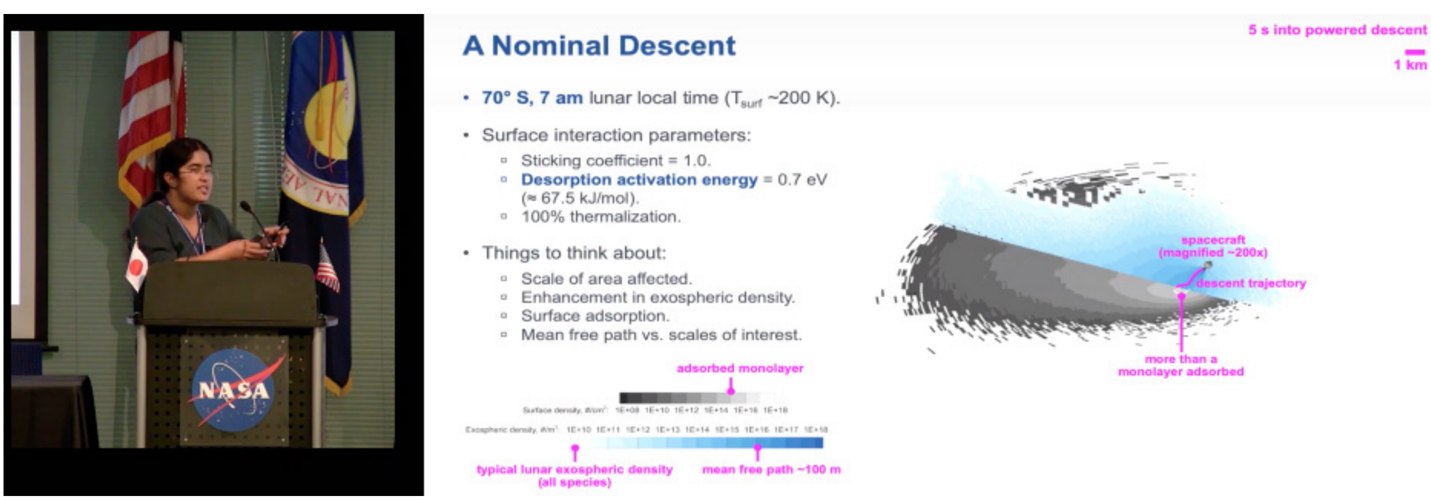


Figure 2. Parvathy Prem at the Forum showing her recent simulation results of gas-surface interactions from a lunar lander exhaust plume.

compete for time with other projects to examine the lunar exosphere. The dedicated lunar sodium observatory at Winer allows for observation on clear nights completely independent of competing priorities, thereby creating the consistent and large baseline to comparing with solar storm activity.

At the 2019 Forum, Farrell et al. (2019) presented a study of the minimum sensitivity of a water-detecting mass spectrometer onboard a lunar orbiting spacecraft as a function of spacecraft outgassing. Spacecraft emit water but some of this water is backscattered by both the water-water and water- lunar exosphere interactions. This backscattered component then defines a minimum sensitivity for any lunar exospheric water detection.

1.3 Radiation Environment and Humans

The DREAM2 radiation team continued to explore how changes in the space radiation environment affect both the Moon and any astronauts on, or near, the Moon. This environment is dominated by two populations of energetic charged particles. Galactic cosmic rays (GCRs) originate outside the Solar System, and their fluxes are controlled by the Sun's heliospheric magnetic field. GCRs are always present in deep space and are very penetrating (to ~1 m). Solar energetic particles (SEPs), on the other hand, are sporadic, being accelerated in the shocks of solar flares and coronal mass ejections. When they do occur, they have much higher fluxes than GCRs.

Rahmanifard et al. (submitted to *Space Weather*) showed that the Sun's overall activity has been declining in a way similar to past secular minima, which are multiple solar cycles with reduced activity. They found a correlation relating the heliospheric magnetic field, the solar wind speed, and the solar modulation of GCRs. This correlation enabled them to predict that the GCR radiation doses in the next solar cycle—cycle 25—will likely be higher than the already elevated levels measured during cycle 24. By using two past secular minima (in 1790–1830 and 1890-1920), the team found that, in deep space, the most conservative permissible mission duration is ~300 days for male and ~200 days for female astronauts, based on a 3% risk of exposure-induced (REID) at the upper 95% confidence interval.

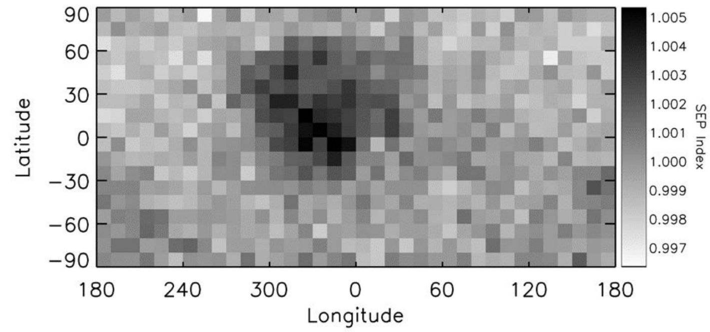


Figure 3. Lunar map of the SEP Index with 10°x10° binning. The highlands and the South Pole Aitken Basin have higher levels of secondary radiation. (From Wilson et al. [in press].)

Wilson et al. (in press) created an SEP Index that robustly identifies SEP events from lunar orbit, using the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter (LRO). During SEP-quiet times, this technique measures the radiation that GCRs eject from the Moon: gamma rays, neutrons, and protons (see Fig. 3). This secondary radiation may be hazardous for astronauts on the surface. The team is continuing to work on what sources dominate this radiation and how it depends on composition.

The team has also shown how SEPs may cause dielectric breakdown weathering in lunar soil (Jordan et al., 2019). They predicted that breakdown weathering may be, on a global scale, comparable to micrometeoroid weathering. Breakdown should be enhanced near the poles, may depend on composition, and may be inhibited by magnetic anomalies, which can block some SEP electrons. Team member Jordan has been searching for such observational signatures in data sets from a number of missions.

1.4 Surface Interactions

The harsh space environment—including impactors, energetic plasma, and radiation— weathers and erodes the regolith-rich surfaces at the Moon and other airless bodies. In PY 6, DREAM2 team members further examined the surface response to this environment.

Specifically, Farrell et al. (2019) published a study on the stability of the LRO/LAMP-observed frost in polar craters to environmental effects like plasma sputtering, impact vaporization, and impact ejection. They found that the top 500 nanometer layers of icy-regolith like that detected by

LAMP have a lifetime of < 10 kyrs – indicating that this frost is all relatively new and dynamic. They presented calculations of the water ejected into the exosphere by these processes that could be sensed by future passing orbital mass spectrometers.

Two new studies were performed in the dedicated DREAM2 beam line at the GSFC Radiation Effect Facility. First, McLain et al. (2019) led a study of the solar wind implantation and hydroxyl formation in regolith samples. He specifically compared the implanted OH signature from fused silica to Apollo regolith samples, and found that the latter had a spectrally broader OH absorption feature near 3 microns. The broadening was due to a combination of the minerology mixture in the sample and space weathering that altered the trapping potential structure of the hydrogen-oxygen bond. The work was presented at the 2019 Forum and the associated manuscript is under review. See the video on this project that also shows the beam line operations at https://www.youtube.com/watch?v=hJMsgRnb1JU&feature=youtu.be

Second, McLain led a study on the solar wind electrical dissipation of space suit material provided by JSC. The JSC collaborators were funded via an internal IRAD, and SSERVI funded the use of DREAM2 resources. Specifically, JSC provided samples with new electrical dissipative coatings to improve the suit's electrical connection to the space plasma environment (the suits are electrically 'grounded' to the plasma and good electrical connection is needed to reduce differential charging on the suit itself). Four suit samples were tested for outgassing and then placed in the dedicated beam line. Each sample underwent exposure to a solar wind-like ion beam and the resulting charge build-up and dissipation was monitored. The results show that the samples with the dissipative coatings remediate charge buildups. However, one sample of the control group (without the coating) also displayed dissipative properties based on its intrinsic composition – suggesting that dissipative coatings may not be necessary if the sui is made of this specific sample material.

Hartzell (2019) published a study of dust levitation at a small Bennu-sized asteroid. She found that the dust could be levitated and migrate across the asteroid's dayside, but escapes the body at the terminator where surface potentials change polarity.

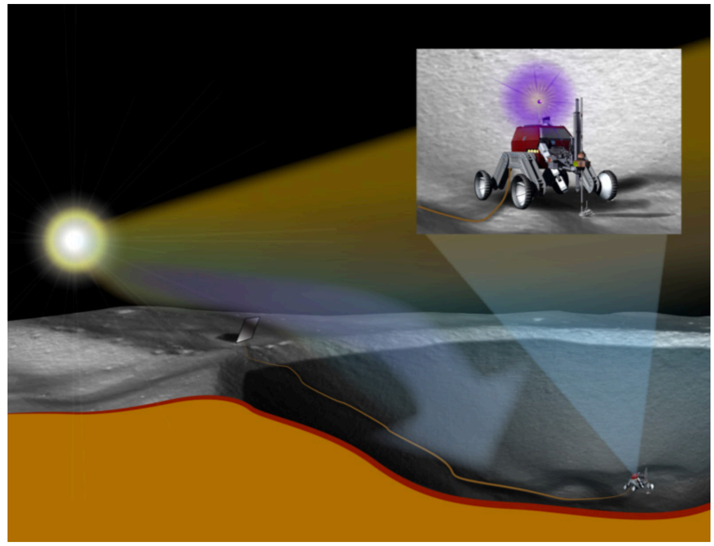


Figure 4. An illustration of a rover drilling into polar crater regolith, and the methods required to dissipate drill-soil tribocharge build-up: a local UV source (see inset) or an electrical connection to a photoelectron-emitting plate located on the crater topside (image credit: J. Friedlander, NASA/GSFC, in Rhodes et al. (2019)).

DREAM2 NPP Dov Rhodes examined the tribocharging expected from a drill operating in the plasma-starved lunar polar crater regions. He found that the drill will charge to large values - close to 1 Megavolt – due to the soil-drill interaction and lack of compensating, dissipating plasma on the polar crater floors. He then described methods for dissipating the charge via local UV light or connecting the entire drill system to a sunlit metal surface located at the crater topside (Figure 4). A paper on this subject has been submitted and is currently under review.

1.5 Support of Lunar Exploration

Given the new directive to get human explorers to the Moon by 2024, NASA is now developing a lunar lander architecture featuring the Gateway station about the Moon and a lunar landing module to transport the explorers to the lunar surface. DREAM2 team members have been called into service at various levels to provide subject-matter expertise in support of these exploration initiatives. This activity includes:

MSFC/DSNE: A number of DREAM2 team members have been working with the MSFC team that is authoring the ‘Design Specification for Natural Environments (DSNE)’ document in support of Gateway and lunar landed activity. The DSNE provides the illumination, thermal, plasma, and micro-meteoroid environment in lunar orbit and at the surface. DREAM2 team members have been providing input on the plasma conditions in the solar wind, geomagnetic tail and on the lunar surface. Former DREAM2-funded graduate student, Heidi (Fuqua) Haviland, from Berkeley, is now working as a civil servant at MSFC in support of these efforts. She has accessed, via A Poppe, THEMIS-ARTEMIS data for the MSFC team to perform statistical analysis of the near-Moon plasma environment. Team members have also provided descriptions of the lunar surface plasma environment based on our plasma expansion models and these results have been incorporated into the DSNE.

JSC/xEVA: DREAM2 team members have also been working in support of the xEVA team at JSC in both space suit dissipation studies and on defining the surface plasma environment at the Moon. In the fall of 2-19, Farrell gave a presentation to the xEVA team in the complex electrical character of the south polar regions where horizontally-flowing solar wind plasma undergoes orographic deviations due to local topography.

NESC Lunar Dust Workshop: The NASA Engineering & Safety Center (NESC) hosted a workshop on lunar dust in February, 2020, and the DREAM2 team submitted a number of abstracts on tribocharging (Hartzell), conductive space suits (Farrell. T Stubbs gave an invited presentation on the dusty exosphere environment.

AES/NextSTEP: The Next Space Technologies for Exploration Partnership (NextSTEP) program funds the build of the joint Morehead St/GSFC Lunar IceCube cubesat to be launched as part of Artemis-1 (formerly EM-1). GSFC is building the IR sensor to fly on the Morehead St. cubesat bus and the system is undergoing environmental testing. See https://www.nasa.gov/feature/goddard/2019/lunar-icecube-mission-to-locate-study-resources-needed-for-sustained-presence-on-moon.

CLPS program: DREAM2 team members have been very actively involved in the Commercial Lunar Payload Services program, with DREAM2 environmental themes driving payload science justifications. These CLPS payload activities include:

Radio wave Observations at the Lunar surface of the photo-Electron Sheath (ROLSES) - PI R. MacDowall/GSFC

- Fly a GSFC built software digital radio to sense the density of the photoelectron sheath. Motivated by DREAM2 photoelectron studies
- DREAM2: Farrell, MacDowall (collaborator)

Near IR Volatile Spectrometer System (NIRVSS) – PI A. Colaprete

- Spectrometer to examine the concentration of surface volatiles from a landed station
- DREAM2: Colaprete

Surface and Exosphere Alteration by a Lander (SEAL)- PI M. Benna/GSFC

- GSFC mass spectrometer to measure the surface outgassing near the landing area. DREAM2 models of a ‘sticky’ sorption gas-surface interface used in support of proposal
- DREAM2: Hurley, Prem, Farrell

Neutron Spectrometer System (NSS) - PI R. Elphic

- Neutron spectrometers to measure the subsurface hydrogen abundance
- DREAM2: Elphic

PROSPECT Ion Trap Mass Spectrometer (PITMS) – PI B. Cohen/GSFC

- Use EM model of the ROSETTA MS for a lunar lander flight to sense human contamination and natural exosphere. DREAM2 models used to support proposal
- DREAM2: Farrell

Landed Magnetometer – PI M. Purucker/GSFC

- Fly the GOES spare DC magnetometer on a lander
- DREAM2: Stubbs, Farrell

Lunar Surface Electromagnetics Experiment (LuSEE) – PI S. Bale/UCB

- Fly the Solar Probe spare Fields package to the lunar surface. Includes a GSFC magnetometer as well
- DREAM2: Poppe, Halekas, Bale (collaborator), MacDowall (collaborator)

Lunar Environment Heliospheric X-ray imager (LEXI) - PI B. Walsh/BU

- Fly a GSFC-built soft x-ray system to look at exosphere emission. X ray system built in DREAM2's M. Collier's lab. Collier's 2014 discovery paper of lunar exosphere soft x-rays was a DREAM2-funded study
- DREAM2: Collier

1.6 Conclusions

Even though PY6 fell mostly under a no-cost extension, DREAM2's momentum from previous years carried the activity well into this period. DREAM2 made great strides in understanding the space environment's effect on the surfaces of airless bodies, and the three-way interaction between the surface response, environmental drivers, and human systems. Given our vast DREAM2 assets, now part of the LEADER program, the team remains poised to assist the exploration of the Moon by humans and in part via commercial landers. The potency of DREAM2 is shown in the numerous CLPS payloads initiated and supported by DREAM2 team members -- and in many cases with SSERVI providing the resources to generate the scientific justification (in the form of science goals and measurement objectives) for these payloads.

2. Inter-team/International Collaborations

2.1 SSERVI Teams

DREAM2 team members are in continual contact and collaboration with other SSERVI teams, science mission teams, and Exploration architecture teams. Examples of DREAM2 interactions with other SSERVI teams include:

REVEALS: DREAM2 PI Farrell is part of the REVEALS Science Advisory Board and the team works together on modeling and lab efforts regarding solar wind implantation and surface hydroxylation at the Moon and other airless bodies. The two teams share **NASA Post-doc Micah Schaible funded via SSERVI-Central NPP award** to perform lab work on the biochemistry and electrical passivity of irradiated surfaces.

NESS: DREAM2 and NESS share collaborators in understanding and assessing the space environmental effects on a sophisticated and sensitive radio astronomy system. We currently supported NESS colleagues on assessing the lunar dust and electrostatic environment, and how to better ground the radio system.

TREX DREAM2 team members Hurley and Farrell are working with TREX PI Hendrix on the UV signature of surface water at the Moon. REVEALS team members are also involved.

VORTICES: Our team shares strong collaborating work on solar wind/airless body interactions, volatile interactions, and Orion/asteroid interactions and lunar pits. Our strongest collaborations are with individuals Zimmerman, Hurley, Prem, & Hibbitts.

RISE4: DREAM2 shared strong collaborating work on lunar pits, with the RISE4 field team providing lidar input to pit environment models shared by DREAM2 and VORTICES. We are working with RIS4E team to pursue opportunities to architect, design and build future exploration-oriented field instrumentation for astronaut use. DREAM2 team members also are collaborators on irradiated grain reactive chemistry that feeds into RIS4E's grain cell survivability work.

IMPACT: DREAM2 maintains strong cross-team collaboration including post-doc opportunities for students, like A. Poppe who did his thesis work under CCLDAS and is now a key DREAM2 team member. **Currently, Anthony Rasca, a former CU grad student, is now a DREAM2 postdoc at GSFC.** DREAM2 modelers (Poppe, Zimmerman) worked with IMPACT team members (Daca, Wang) on magnetic anomaly and grain-grain surface charging studies.

FINESSE: DREAM2 share Co-Is Colaprete and Elphic, who under FINESSE perform field studies for the lunar rover missions, while DREAM2 provides support with modeling studies on wheel-regolith interactions and volatile transport modeling.

2.2 International Partners

Sweden: DREAM2 team members continue close interactions with investigators at the Swedish Institute of Space Physics in Kiruna, Sweden. DREAM2 Co-I Shahab Fatemi relocated from UCB to Kiruna and is working closely with DREAM2's NPP Anthony Rasca in modeling the plasma flow about the Moon in the geomagnetic tail.

3. Public Engagement Report

3.1 Undergraduate Internship Program: Howard University and DREAM2

Public Engagement efforts, led by Co-I Dr. Prabhakar Misra at Howard University, primarily involved recruiting undergraduate students from Howard University for summer research internships at NASA Goddard, and the continued mentoring of these students at Howard University. Financial support for the undergraduate student interns from Howard University was built into the NASA Goddard Internship Program budget for the DREAM2 project. Dr. Misra continued to leverage the DREAM2 effort with the NASA MUREP project titled "NASA Early Opportunities Program for Underrepresented Minorities in Earth & Space Sciences," which supports part-time research for undergraduate STEM students from Howard University with NASA Goddard mentors during the academic year, with full-time, on-site research during the summers.

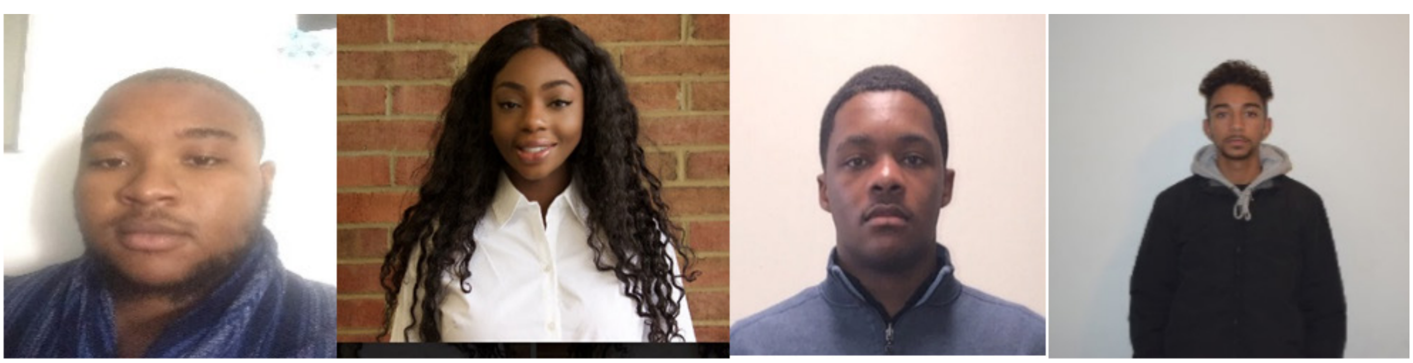
Here are representative samples of the research projects pursued by the Howard University students during the period March-December 2019, with expert guidance from NASA GSFC DREAM2 mentors.

1. Skylar Grammas (Major: Computer Science; Student Status: Senior): "Development of Visualization Tools in Support of the DSX Tri-Axial Search Coil" (NASA GSFC Mentor: Dr. William Farrell/Code 695)
2. Irima Ajang (Major: Sports Medicine, Minor: Chemistry; Student Status: Senior): "Remote Observations of the Lunar Sodium Corona" (NASA GSFC Mentor: Dr. Rosemary Killen/Code 695)
3. Essien Taylor (Major: Computer Engineering; Student Status: Sophomore): "Analysis of Magnetopause Models Using Observed Magnetopause Crossings" (NASA GSFC Mentor: Dr. Michael Collier/Code 673)
4. Elijah Catalan (Double Major: Biology & Environmental Studies; Student Status: Senior): "Modeling Neon Distribution in the Lunar Exosphere: a Comparison to LACE Data" (NASA GSFC Mentor: Dr. Orenthal Tucker/Code 695)

3.2 DREAM2 Support of Public Engagement Activities

In 2019, the DREAM2 team was involved in number of public engagement activities, including:

Apollo 50th Anniversary: DREAM2 representatives Nikki Whelley and Andrea Jones were involved in organizational efforts with HQ in event planning and coordination across the nation in preparation for the anniversary. This included a website where baseball teams, national parks, and other large groups could find activities and resources tailored to their spaces and visitors. The DREAM2 E/PO team coordinated and ensured NASA/GSFC representatives were present at various sites of activity like the celebration at the National Mall, and the McAuliffe Shepard Discovery



Skylar Grammas Irima Ajang Essien Taylor Elijah Catalan

Fig. 5. Howard University students involved in the DREAM2 internship program

Center in New Hampshire, where they shared DREAM2/LEADER environmental science with the public.

International Observe the Moon Night (IOMN): This event occurred on October 5, 2019, and DREAM2/LEADER members Andrea Jones and Nikki Whelley were organizers of the international team. The team worked to encourage people all over the world to look up at the Moon, ask questions, and learn about current space science. The world-wide participation was estimated to be upwards of 250,000 people in 2019. GSFC held an advertised event at the GSFC Visitor Center, with over 500 people attending. Telescopes were set up for public viewing and lectures given on the Moon, Apollo missions, and space science in general.

MICA Collaboration: DREAM2 team member Dov Rhodes teamed up with students from the Maryland Institute College of Art (MICA) to create a new and unique animation of the electrical characteristics of the Moon. A final project was presented that featured the new animation.

4. Student/Early Career Participation

Undergraduate Students

DREAM2 Co-I Prabhakar Misra at Howard University won a NASA award to fund a number of undergraduates for a 4-year internship with DREAM2 and others at GSFC. The Award is "NASA Early Opportunities Program for Underrepresented Minorities in Earth and Space Sciences" (PI: P. Misra, Howard University; Co-PIs: D. Venable, Howard University; B. Meeson, NASA Goddard; S. Hoban, UMBC; & B. Demoz, UMBC; 8/1/16-7/31/19). The HU students and their projects are described in Section 3.1.

Graduate Students

- Stephanie Howard, Iowa, Solar wind magnetic anomaly plasma disturbances at the Moon
- Philip Quinn, UNH, Radiation
- Fatemeh Rahmanifard, UNH, Radiation

Postdoctoral Fellows

- Charles Lue, Iowa, Space plasma and ARTEMIS
- Xin Cao, Iowa, Lunar plasma interactions in the magnetotail
- Dov Rhodes, GSFC, Charging on human systems
- Anthony Rasca, GSFC, Inner heliospheric plasma flow at small bodies
- Parvathy Prem, APL, Exospheres and collisional atmospheres
- Micah Schaible, Ga Tech, DREAM2-REVEALS SSERVI NPP, biochemistry and passivity of irradiated grains
- Quentin Nénon, UC Berkeley, Sputtering and exo-ions at Phobos

5. Mission Involvement

Shown below are DREAM2 team member roles on current and planned missions. (PSD= NASA's Planetary Science Division, HSD= NASA's Heliophysics Science Division, AES=NASA's Advanced Exploration Systems Division)

PI, Co-I, and Guest Investigator roles (* = DREAM2 collaborator):

1. PSD/CLPS/Collier/Co-I and Instrument Lead LEXI
2. PSD/CLPS/Colaprete/PI of NIRVSS
3. PSD/CLPS/Hurley/Co-I on SEAL
4. PSD/CLPS/Elphic/PI of NSS
5. PSD/CLPS/Stubbs/Co-I on MAG
6. PSD/CLPS/Bale*/PI on LuSEE
7. PSD/CLPS/Poppe/Co-I on LuSEE
8. PSD/CLPS/Halekas/Co-I on LuSEE
9. PSD/CLPS/MacDowall*/PI of ROLSES, Co-I on LuSEE
10. PSD/CLPS/Farrell/Co-I on ROLSES, PITMS, SEAL, MAG
11. PSD/Lunar Reconnaissance Orbiter/Petro*/Project Scientist
12. PSD/Lunar Reconnaissance Orbiter/ Keller/Deputy Project Scientist
13. PSD/Lunar Reconnaissance Orbiter/Schwadron/CRaTER PI

14. PSD/Lunar Reconnaissance Orbiter/Spence/CRaTER Co-I and former PI
15. PSD/ Lunar Reconnaissance Orbiter/Jordan/CRaTER Co-I
16. PSD/ Lunar Reconnaissance Orbiter/Wilson/CRaTER Co-I
17. PSD/Lunar Reconnaissance Orbiter/Hurley/LAMP Co-I
18. PSD/ Lunar Reconnaissance Orbiter/Elphic/Diviner Co-I
19. PSD/Lunar Reconnaissance Orbiter/Stubbs/ Participating Scientist
20. PSD/LADEE/Elphic/Project Scientist
21. PSD/LADEE/Delory/Deputy Project Scientist
22. PSD/LADEE/Colaprete/UVS PI
23. PSD/LADEE/Hodges/NMS Co-I
24. PSD/LADEE/Stubbs/Guest Investigator
25. PSD/LADEE/Glenar/Guest Investigator (named on the Stubbs' GI proposal)
26. PSD/LADEE/Hurley/Guest Investigator
27. PSD/LADEE/Halekas/Guest Investigator
28. PSD/LADEE//Poppe/Guest Investigator (named on Halekas' GI proposal)
29. PSD/LADEE/Sarantos/Guest Investigator
30. PSD/OSIRIS REx/Marshall/Co-I and former lead of Regolith Working Group
31. PSD/OSIRIS REx/Nuth*/Deputy Proj Sci
32. PSD/OSIRIS REx/Lim*/Co-I
33. PSD/OSIRIS REx/Hartzell*/Participating Scientist
34. PSD/Phoenix/Marshall/MECA Co-I
35. PSD/MAVEN/Delory/Co-I
36. PSD/MAVEN/Halekas/Co-I and lead build of ion spectrometer
37. PSD/MESSENGER/Killen/Co-I
38. PSD/Curiosity/L. Bleacher/Communications
39. PSD/Cassini/Farrell/RPWS/Co-I
40. AES/Lunar IceCube/Clark/Science PI
41. HSD/ARTEMIS/Halekas/Deputy PI
42. HSD/ARTEMIS/Delory/Co-I
43. HSD/WIND/Collier/Deputy PI
44. HSD/WIND/Farrell/WAVES and MFI Co-I
45. HSD/Parker Solar Probe/Farrell/Co-I
46. HSD/Parker Solar Probe/Schwadron/Co-I
47. HSD/IBEX/Schwadron/Co-I
48. HSD/Tracers/Halekas/Co-I and Instrument lead
49. HSD&ESA/Solar Orbiter/Collier/Co-I Heavy ion sensor (GSFC lead)
50. HSD&ESA/SMILE/Collier/Co-I
51. HSD/CuPID cubesat/Collier/Co-I and instrument lead
52. ESA/BepiColumbo/Killen/Co-I
53. ISRO/Chandrayaan-1/Holmstorm*/Co-I
54. JAXA/MMX/Elphic/MEGANE Co-I
55. KARI/KPLO/Elphic/KGRS Co-I
56. DoD (Space Test Program)/FASTSAT/Collier/Co-I and instrument lead
57. DoD (Space Test Program)/USAF DSX/Farrell/Co-I and search coil build lead

Mission-recognized supporting roles includes:

58. PSD/CLPS/Prem/Modeling support of SEAL
59. PSD/Lunar Reconnaissance Orbiter/Glenar/LAMP data analysis
60. PSD/ Lunar Reconnaissance Orbiter/Prem/Diviner and Mini-RF data analysis
61. PSD/LADEE/Marshall/UVS instrument calibration
62. PSD/Cassini/Cooper/CAPS team member, data analysis
63. PSD/Cassini/Hurley/Enceladus modeling
64. HSD/ARTEMIS/Poppe/plasma data analysis
65. HSD/ARTEMIS/Fatemi/plasma data analysis & modeling

Field Investigations to Enable Solar System Science and Exploration (FINESSE)

Jennifer Heldmann
NASA Ames Research Center

1. FINESSE Team Report

1.1 Rheology of a KREEP Analog Magma: Experimental Results Applied to Dike Ascent Through the Lunar Crust

Apollo returned samples included basaltic rocks belonging to the KREEP suite, which are thought to have been erupted ~4.1 – 3.9 bya via dike propagation from the residual magmatic layer residing below the lunar crust as the last part of the solidifying lunar magma ocean. The emplacement dynamics of KREEP magma reaching the lunar surface are generally poorly understood, in part because no rheological data are available to model the conditions of KREEP ascent in detail, even ~50 years after KREEP basalt discovery. This study provides the first rheological data for KREEP magmas, as a function of temperature and crystal content, from the liquidus temperature (~1205 ºC) to ~16% crystals by volume at ~1177˚C. The lava's rheological behavior becomes non-Newtonian at just a few degrees of cooling below the liquidus and is well represented by a shear-thinning power-law equation. We applied these data to a buoyancy-driven dike ascent model (Figure 1), suggesting that if KREEP magma ascended through dikes comparable in size to those that fed the lunar mare, it most likely erupted below its liquidus in the range of 1180 ºC to 1160 ºC, with effective viscosities in the range 10^3 to 10^7 Pas and traversing the lunar crust on timescales of minutes to hours.

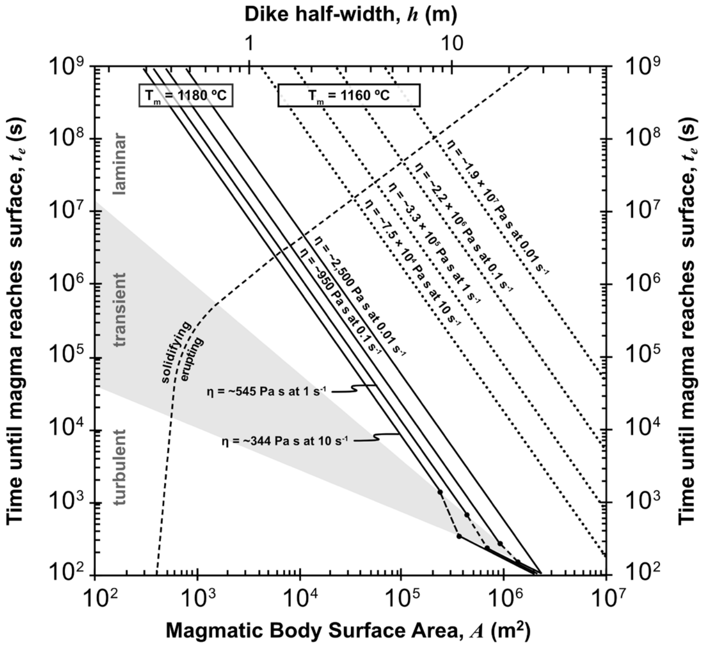


Figure 1. Dependence of the eruption time t_e on the magma area A for KREEP erupting from a depth of 30 km for a dike aspect ratio of 10^3. Calculations are given for several magma viscosities at 1180 ºC and 1160 ºC and different strain rates as indicated. Results are shown for laminar and turbulent flow, which is divided by the gray field representing the transient flow regime. The dotted line represents solidification; solutions to the left would be expected to solidify and those to the right would be able to erupt.

1.2 Thermal Properties of Glassy and Molten Planetary Candidate Lavas

Heat transport plays a crucial role in igneous processes, and the thermal evolution of the interiors of terrestrial bodies. Thermal conductivity is a product of density (ρ), thermal diffusivity (*D*) and heat capacity (C_P). We measured *D* and C_P as a function of temperature for a suite of planetary analog lavas relevant to the Moon, Mars, Mercury, Io and Vesta. Heat capacity measurements were conducted by differential scanning calorimetry (DSC) on glasses and liquids covering temperatures from 400 to 1750 K, D measurements were conducted by laser-flash analyses (LFA) on glasses from room temperature up to their melting point slightly above the glass transition (T_g), and densities were already known. Our results demonstrate that the variability of *D* and C_P is very composition-specific, making thermal conductivity ($k = D\rho C_p$) strongly composition-dependent. We present an empirical model to estimate D of glasses as a function of temperature and composition, with 2σ uncertainty of 0.040 $mm^2\ s^{-1}$. Thermal diffusivity of the corresponding melt can be calculated with an uncertainty of 0.044 $mm^2 s^{-1}$, but only independent of temperature. The model for D presented here, in combination with already available models to calculate C_p and ρ, allows us to predict thermal conductivity for a wide range of compositions for glasses and melts relevant to major planetary objects in the Solar System. We show that basaltic liquids have thermal conductivities between 1.0 and 1.7 $Wm^{-1}K^{-1}$, about half that of the mantle from which they are generated, and therefore partial melting of ascending mantle leads to a positive feedback that promotes high melt fractions. The chemical dependence of k suggests that this effect may have been more or less effective on different planetary bodies and at different times in their evolution.

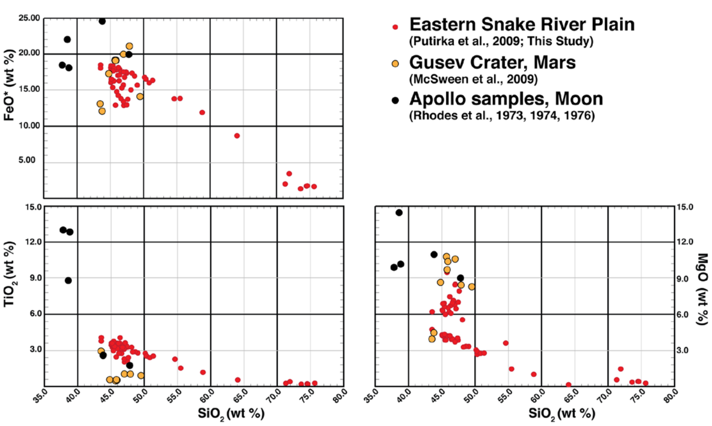


Figure 2. Chemical variation of Eastern Snake River Plain (Earth), Gusev Crater (Mars), and Apollo samples (Moon).

1.3 Ferrobasalt of the Snake River Plain as an Analog to Lunar Ti-bearing Volcanics

The Snake River Plain (SRP) is host to extensive intra-plate volcanism characterized by a bi-modal distribution of tholeiitic basalt and potassic rhyolite. Rare compositionally intermediate lavas are located in Craters of the Moon (COTM) National Monument and Preserve in Idaho, USA and represent fractionated liquids evolved from the same parental magma which gave rise to the

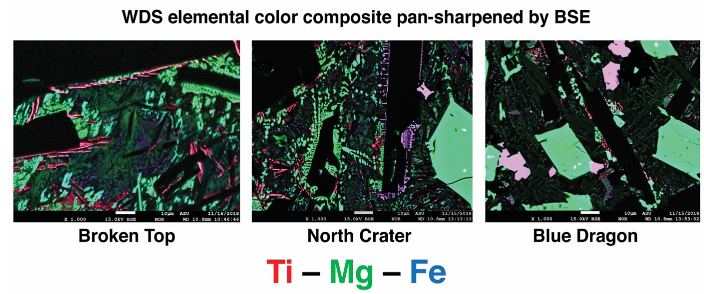


Figure 3. Petrographic analysis of COTM ferrobasalts.

tholeiitic plains basalts common on the SRP. Chemically, the SRP suite exhibits a tholeiitic differentiation trend with initial fractional crystallization leading to synchronous enrichment of Fe and Ti in the residual liquids. Abundances reach peaks of ~19.0 (FeO_{total}) and ~4.0 wt% (TiO_2) before rapidly diminishing in more evolved lavas (Figure 2).

It has been shown experimentally that coupled Fe-Ti enrichment and depletion trends are the result of ilmenite ($FeTiO_3$) saturation and fractionation (Juster et al. 1989). Detailed petrographic analysis of COTM ferrobasalts reveals two populations of Fe-Ti oxides; 1) clusters of octahedral titanomagnetite microphenocrysts (10-50 μm) set in a glassy opaque groundmass and 2) acicular to feathery ilmenite crystallites (<10μm) mantling larger feldspar and olivine microphenocrysts. Ilmenite crystals likely grew rapidly as the ferrobasaltic magma was erupted near ilmenite saturation and rapidly cooled, consistent with the high glass contents observed.

Visible near-IR reflectance spectra of the COTM ferrobasalts (Figure 4) are characterized by an absorption near 590 nm with a smooth red-sloped spectrum >1000 nm with very weak absorptions near 1050 and 1200 nm. These bands can be assigned to a Fe^{2+}-Ti^{4+} charge transfer absorption from ilmenite (590 nm) and Fe^{2+} crystal field absorptions in olivine (1050 and 1200 nm).

The presence of fine-grained ilmenite mantling phenocrysts in the COTM ferrobasalts results in a spectrum dominated by ilmenite with little evidence for olivine, despite the presence of approximately 10-15% olivine by volume. A similar petrographic texture, described as olivine needles/microlites set in a glassy matrix and mantled with feathery ilmenite, was observed in the black vitrophyric beads found in the Apollo 17 soil (74001/74220) near

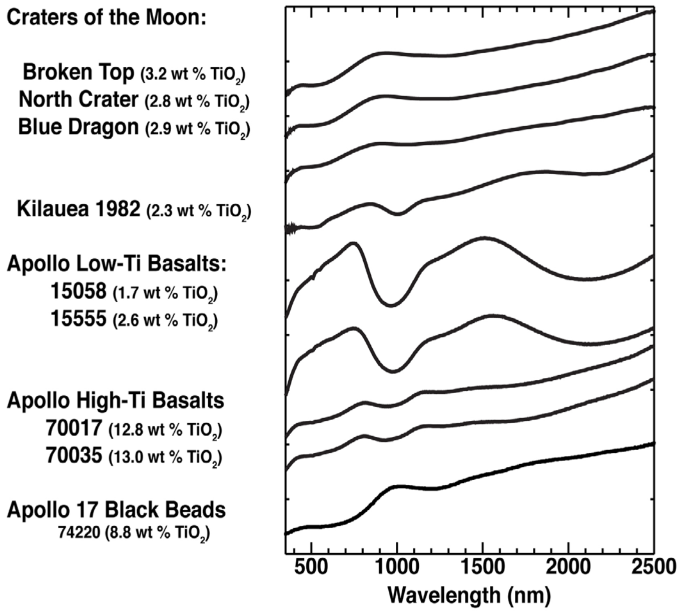


Figure 4. Visible-near infrared reflectance spectra of COTM ferrobasalts compared with lunar and Hawaii samples.

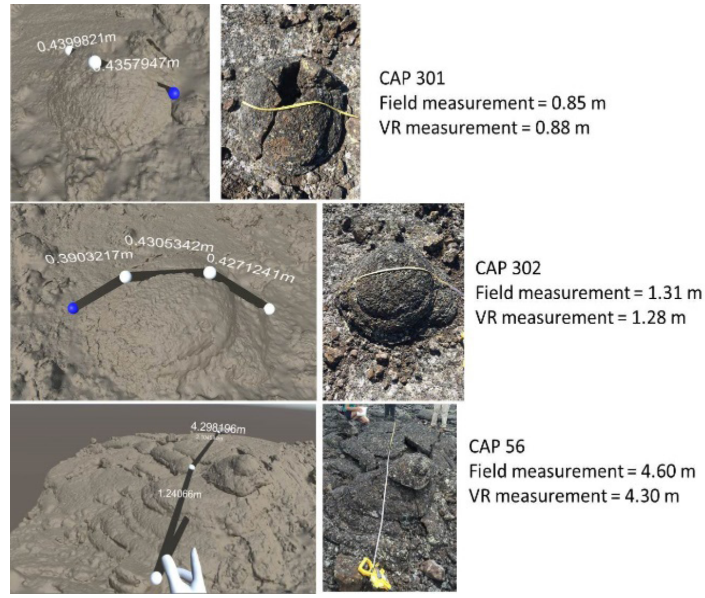


Figure 5: Test measurements collected in a VR environment (left) compared to field measurements collected in Idaho (right).

Shorty crater and the VNIR spectra also show striking similarities to the COTM ferrobasalts. The returned Apollo samples that express a similar Fe^{2+}-Ti^{4+} charge transfer absorption near 590 nm host significantly more bulk TiO2, and by inference ilmenite, than the COTM ferrobasalts. Ilmenite is an important target mineral for lunar ISRU (in situ resource utilization) and these results indicate that remote sensing investigations searching for ilmenite-rich deposits could be inaccurate if some lunar rocks exhibit petrographic textures similar to those observed in COTM.

1.4 Using Virtual Reality Field Studies to Enable Analog Research of Planetary Surfaces and Self-Secondary Cratering Processes

The FINESSE team, in partnership with the VORTICES team, is working on a project that uses Virtual Reality (VR) field studies to enable analog research of planetary surfaces. The project is driven by three main focuses – science, operations and technology. Our science focuses on analyzing self-secondary impact features at Kings Bowl (in a VR environment), as an analog for self-secondary impact features within impact melt ponds on the Moon. The VR environment is created by LiDAR data collected by the FINESSE team at Kings Bowl. Field data of self-secondary impact features at Kings Bowl is used to ground-truth the same features visible in the VR field site. The operations are focused on documenting and evaluating best practices for decision-making protocols, traverse planning, field data acquisition and recording, data flow protocols, and best practices for navigating through the VR field-site. We chose to investigate the efficacy of VR as a key technology to enable and optimize future planetary fieldwork for a variety of reasons. For example, VR platforms can allow fieldwork to be conducted at lower project cost (fewer people having to travel to remote field sites for extended periods of time for fieldwork). VR can also democratize planetary fieldwork and allow individuals to participate in fieldwork science activities who may otherwise be precluded from doing so due to physical limitations (e.g., physical inability to effectively operate in the often difficult conditions of a terrestrial analog field setting).

Initial results show agreement between in-situ field measurements and VR field measurements (Figure 5). Over 300 features were measured in the field and these are being compared to the same features in the VR field site. Future work includes conducting more field work in VR, making direct comparisons with operations for in-situ field studies (e.g., time spent traversing from one feature to another can be compared to time-stamped photos from

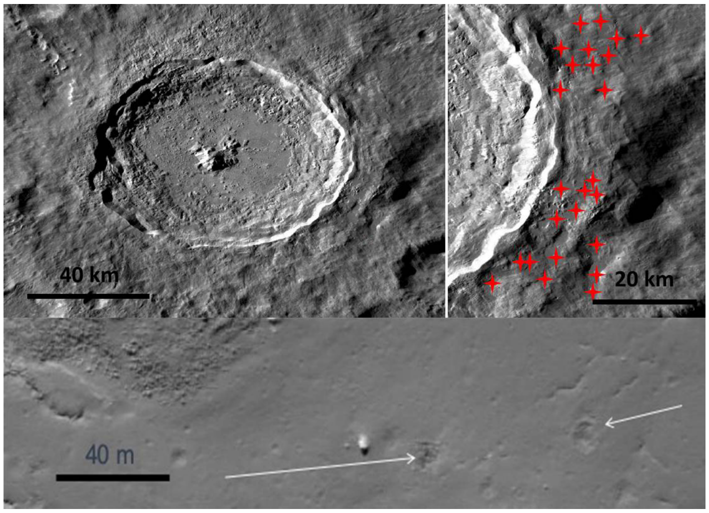


Figure 6: Upper left: LROC image of Tycho Crater. Upper Right: Red stars are location of 25 impact melt ponds on the eastern ejecta blanket of Tycho, chosen for this work. Lower: White arrows point to splash craters in impact melt.

the Kings Bowl field site), and studying the self-secondary features as an analog for self-secondary features within impact melt ponds on the Moon (Figure 6).

1.5 Human Performance in Extreme Environments

The FINESSE program researched human performance in extreme environments to optimize human performance on other planetary bodies, and included research from multiple successful analog field deployments in Idaho and Hawai'i. The initial testing of remote physiological monitoring capabilities during initial FINESSE operations was critical in enabling physiological data recording and live display of multiple EVA crew members over multiple day deployments. This proof of concept and incorporation of physiological monitoring for IV (intravehicular) crew member operations was also important to help determine crew member workload, situation awareness, and task prioritization considerations that will be important for future human-machine function allocation and agent-based decision support concerns for EVA crew health monitoring.

Multiple technical publications (as well as NASA outreach and engagement presentations) have resulted from this effort. In particular, graduate student Jordan Hill completed her MS and PhD research at Purdue University based on the analog field deployments initiated under FINESSE. Dr. Hill completed her MS thesis on the remote physiological monitoring / IV integration proof of concept, and her PhD dissertation on the function allocation and information needs assessment considerations for the design of IV crew member task allocations and human-automation interaction demands for human exploration of Mars.

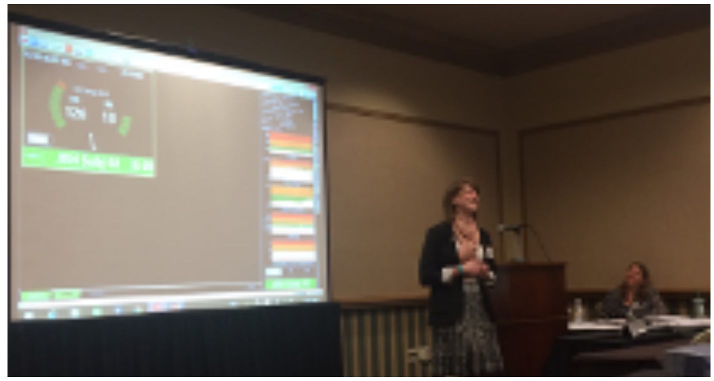


Figure 7. Jordan Hill live demos remote physiological monitoring capabilities at HRP IWS, Galveston, TX.

1.6 Intrinsic Geochemical Variability in Volcanic Rift Zones – Terrestrial Analogs for Magma Evolution in Sill and Dike Networks on the Moon

Field and laboratory analyses of lava flows at COTM in Idaho, Kilauea Volcano on the Big Island of Hawai`i, and the 1975-1984 Krafla Fires fissure eruptions in Iceland help improve the methods of surface exploration applied to planetary volcanic features. Complexities in magmatic sources and processes of magma mixing and evolution must occur in sill and dike networks (magma reservoirs) that comprise active eruptive fissures. We postulate that multiple reservoirs are important to lunar magmatic systems (Figure 8). To address this further we selected

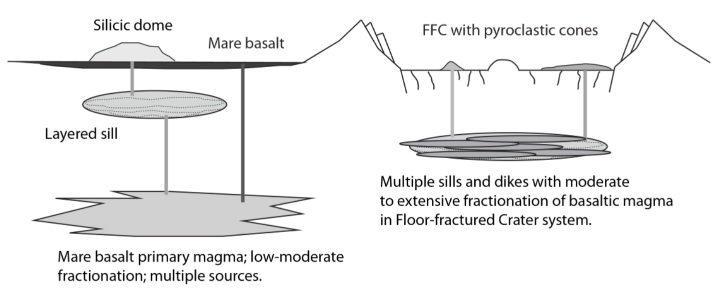


Figure 8. Schematic models of possible subsurface magmatic processes occurring within complex sill and dike networks on the Moon that lead to diverse compositions in magmas related to silicic domes, mare basalts, and floor-fractured craters.

regions separate from COTM for field work and sample analysis. Analog targets at Kilauea, which include East Rift Zone eruptions at Mauna Ulu and Kilauea Iki, and fissure eruptions on the floor of the summit caldera, were sampled in late 2017. We also sampled in May 2018 field targets in Iceland, focusing on the Krafla fissure that erupted in 1975 – 1984 along with several other point sites for comparison.

Current research (Hughes et al., in preparation) focuses on the compilation and assessment of geochemical analyses of the Krafla Fires compared to our earlier examination of geochemical signatures at Kings Bowl and surrounding areas in order to assess geochemical variations within individual eruptions (Figure 9).

Broad trends in geochemical variability within the Kings Bowl flows are not spatially related, which suggests that either the fissure system tapped a single incompletely mixed magma source or that variable mixing occurred along the entire fissure. A more significant issue is the comparison of Kings Bowl geochemistry to neighboring

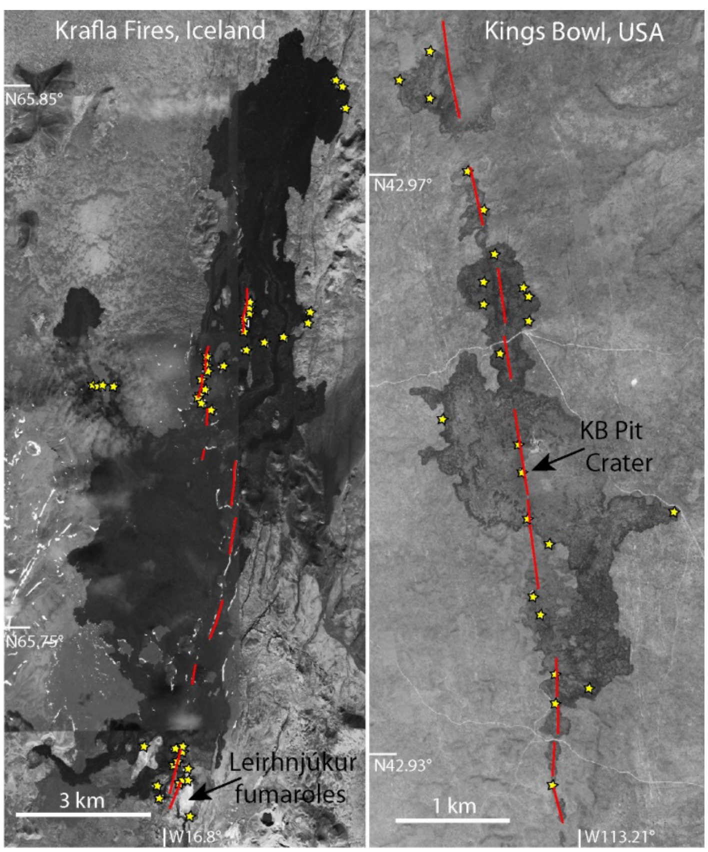


Figure 9. Basaltic lava flows and eruptive fissures (in red) of the Krafla Fires (left) and Kings Bowl (right) systems. Sample locations shown as yellow-filled stars. Base maps are grayscale Google Earth images.

lava fields (Figure 9). Separate geochemical trends possibly derived from different magma bodies are apparent for older pre-Kings Bowl, Wapi and Inferno Chasm lava flows, illustrating the complexities along the southern Great Rift. The geochemistry of Krafla Fires lavas also reveals a tight major element trend that is overall less mafic (lower MgO) than Kings Bowl lavas. The data confirm a strong bimodality recognized previously, which separates a rather primitive (mafic) series from a more chemically evolved series.

This research suggests that the separate geochemical clusters in both systems reflect multiple magma reservoirs, as proposed for Kings Bowl and the Krafla Fires. Monogenetic fissure eruptions on the Moon, Mars or other planetary bodies may have similar magmatic complexities. Petrologic models are currently being investigated to determine possible scenarios for the variations within each eruptive episode.

1.7 Basaltic Fissure Types on Earth: Suitable Analogs to Evaluate the Origins of Volcanic Terrains on the Moon and Mars?

Basaltic eruptive fissures of the Great Rift and surroundings on the eastern Snake River Plain, and selected volcanic features in Hawai`i, Iceland and northern Africa were surveyed for their relevancy as planetary analogs. Evaluated during field investigations and in satellite imagery for structures, physiography, and geologic setting, fissures were categorized into four broad types (Figure 10): (1) simple, monogenetic fissures with obvious volcanic constructs or deposits, (2) monogenetic fissures now obscured by low shields or relatively large cones, (3) polygenetic volcanic rift zones with multiple vents and deposits, and (4) compound regional fissure systems or dike swarms that comprise major rift zones or large volcanic terrains. Using this classification as an initial base, we surveyed imagery of volcanic features for likely fissure vents in two major geologic settings on the Moon: floor-fractured craters (FFCs) and mare and cryptomare provinces. Two major regions on Mars, the volcanic plains around Alba Mons and the greater Tharsis region, were also surveyed for fissure types and volcanic associations of fissure-like features. The planetary surveys suggest that the proposed classification provides

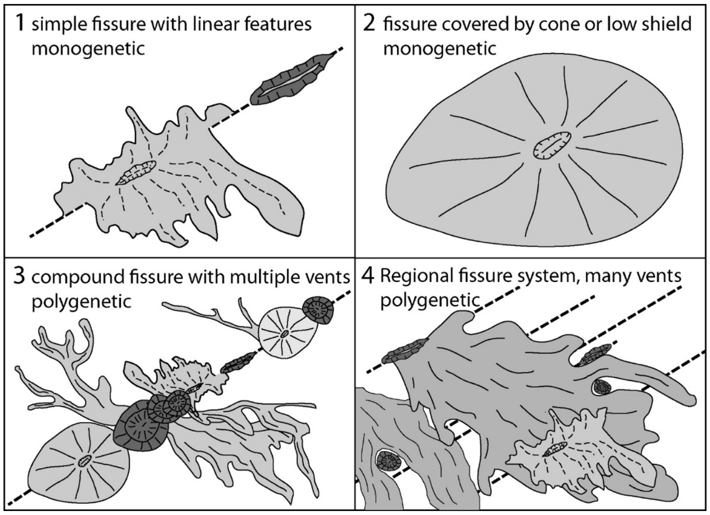


Figure 10. Schematic illustration of basaltic fissure types (variable scales), categorized from Earth analogs. Types 1 – 3 are represented on the ESRP and many other volcanic provinces, while type 4 fissures are associated only with large igneous provinces including major rift zones and flood basalts.

a suitable analog starting point to interpret structures associated with fissure systems on the Moon and Mars.

With few exceptions, our survey indicates that each of the studied terrains exhibits a dominant fissure type. Type 1 fissures, most with pyroclastic deposits, prevail in lunar FFCs and mare-like regions; whereas type 2 fissures, a few on the Moon as low shields, are ubiquitous in the Tharsis region of Mars. Exceptions include Lacus Veris cones on the Moon and some martian type 2 low shields, which have remnant type 1 fissure segments. Type 3 volcanic rifts are not common on either the Moon or Mars; however, two mare type 1 vents, Isis and Osiris (fissure constructs that occur with others on Rima Reiko) are potentially a type 3 volcanic rift. We suggest that other type 3 fissures ultimately may be found in other geologic settings on these planetary bodies. Type 4 fissures are inferred in mare terrains, often represented as the extensions of major linear rille networks or rimae, with possibly complex dike swarms that were buried beneath voluminous mare basalt lava flows. Likewise, numerous flood lavas on Mars are possibly associated with now-obscured or difficult to define type 4 fissure systems. An additional conundrum exists with non-eruptive fissure-like structures. Although located in lava terrains, they may not be true volcanic vents. Examples include a few collapse pits along Rima Hyginus on the Moon and numerous (collapse?) pits within fossae around Alba Mons on Mars. They exhibit key extensional structures of type 1 fissures on vast lava plains, yet have no evidence of direct association to pyroclastic ejecta or lava flows.

Topographic assessment of FFC and mare volcanic vents provides additional implications for volcanism on the Moon (Figure 11). Profiles derived from Lunar Reconnaissance Orbiter Camera (LROC) Quickmap tools are similar over a large range in size. Most of the vents we evaluated have t “V” shaped profiles and characteristic pyroclastic halos. However, volcanic vent sizes in both FFC and mare lunar terrains are similar and nearly span an order of magnitude, with FFC rim-to-rim vent widths ranging from 0.96 – 6.1 km and depths ranging from 45 – 1200 m; and mare-like vent widths ranging from 0.65 – 6.9 km and depths ranging from 22 – 1060 m. Although their size ranges are similar, most FFC vents (with two exceptions) have widths under 3 km and depths less than 400 m, and most mare-like vents are significantly larger. Four FFC candidate volcanic pit craters and one mare pit crater are morphologically distinct with much higher width to depth ratios. Two of them, located in Oppenheimer (S and SW), range from 11.5 – 13 km wide and 770 – 1250 m deep; and, a third crater, Oppenheimer U (38 km wide,

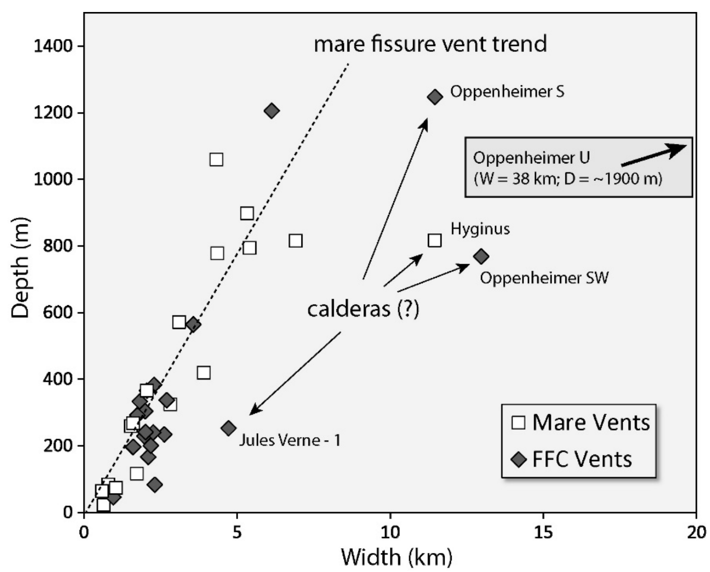


Figure 11. Plot of depth vs. width of fissure vents on the Moon observed in mare-like (including cryptomare) and FFC settings. The nearly linear trend in rim-to-rim widths and rim-to-floor depths likely represent similar volcanic styles with variation in eruptive volumes or explosivity. Craters that fall far off the trend include purported calderas and Oppenheimer U, which is probably an impact crater, that plots outside the field.

1910 m deep), is probably a small impact crater within the larger main crater. One other FFC pit crater, Jules Verne - 1, is 4.7 km wide and 253 m deep; and one mare pit crater vent, Hyginus Crater, is 11.5 km wide and 817 m deep. All five of these craters have flat or irregular floors, and, except for Oppenheimer U impact crater, their high width/depth ratios are similar to collapse pit craters or calderas on large terrestrial shield volcanoes.

The proposed designation of eruptive fissure types 1 – 4, based on Earth examples, provides a preliminary classification for the evaluation of extraterrestrial volcanic processes. The classification can be used to establish the fundamental architecture of fissure systems on other planets, although the types must be broadly defined in order to include myriad variants. More importantly, only the simpler types 1 and 2 are believed to exist in abundance on the surfaces of the Moon and Mars; whereas, types 3 and 4 are either scarce or inferred.

2. FINESSE Inter-team/International Collaborations

2.1 International Collaborations

2.1.1 Canadian Lunar Research Network, University of Western Ontario

FINESSE works closely with team member Dr. Gordon Osinski (University of Western Ontario, UWO) as the lead of the Canadian Lunar Research Network, an official SSERVI international partner. FINESSE has supported the ongoing sample analysis of West Clearwater Impact Structure samples and publication of results regarding WCIS formation, impact melts, shock history, and melt vein development, among other topics. UWO has also conducted fieldwork in Idaho as ground-truthing for radar data studies of the volcanic fields (C. Neish). FINESSE and UWO are also sharing laboratory instrumentation and sample analysis equipment which is beneficial to both parties for enabling this new science pertaining to WCIS.

2.1.2 Carleton University

Carleton University (Ottawa, Canada) is contributing to the study of using gravity data to map and characterize subsurface volcanic structures such as lava tubes. Ground-truthing of such non-invasive remote sensing techniques to identify subsurface voids in volcanic terrains is important not only to the scientific study of our planet and the Moon, but also for identification of possible lunar structures for future exploration.

2.1.3 KIGAM (Korea Institute of Geoscience and Mineral Resources)

FINESSE Collaborator Kyeong Kim is a researcher with the Korea Institute of Geoscience and Mineral Resources. Kim's research focuses on lunar science and the applications of XRF analysis on planetary surfaces. Kim has deployed to both Idaho and Iceland with the FINESSE team. She is also the PI of the gamma ray instrument slated to fly onboard the Korean Pathfinder Lunar Orbiter and has involved FINESSE team member R. Elphic as a Co-I with KPLO.

2.1.4 Indian Institute of Technology Kanpur

FINESSE team member Dr. Deepak Dhingra is an Assistant Professor within the Department of Earth Sciences at the Indian Institute of Technology Kanpur in Uttar Pradesh, India. Dhingra continues to work with the FINESSE team publishing his research findings in collaboration with the FINESSE remote sensing team regarding volcanic features at Craters of the Moon National Monument and Preserve.

2.2 SSERVI Inter-Team

2.2.1 VORTICES

The FINESSE PI has worked closely with the VORTICES PI (A. Rivkin) to include VORTICES Co-I participation in FINESSE fieldwork. VORTICES team member Matiella-Novak participated in the FINESSE Idaho fieldwork and she is also leading a project to incorporate virtual reality into the required field measurements for understanding self-secondary crater formation in Idaho and on the Moon.

2.2.2 RIS4E

FINESSE Volcanics Science Co-Lead Dr. Brent Garry (NASA GSFC) is also a Co-I on RIS4E. In particular, field testing and use of the LiDAR system within both the FINESSE and RIS4E field campaigns has helped to increase the fidelity and operations of this field instrument. FINESSE PI Heldmann, Deputy PI Lim, and RIS4E PI Glotch also co-founded the SSERVI Analogs Focus Group in 2019.

3. Public Engagement Report

3.1 Outreach Activities

The FINESSE team has actively shared our research and interest in planetary science and exploration (Figure 8). In addition to numerous public lectures and seminars, team members have presented research in a variety of venues. As examples, FINESSE PI Heldmann served on a panel at the Metropolitan Museum of Art in New York City to discuss lunar science in honor of the 50th anniversary of Apollo. PI Heldmann also was interviewed on NASA Chief Scientist Jim Green's podcast "Gravity Assist" to discuss lunar volatiles and geology, and she served on a panel discussion organized by the SSERVI Central Office aboard the USS Hornet in July 2019 which recovered the Apollo 11 astronauts after their successful return to the Earth. SSERVI Deputy PI Darlene Lim conducted a tour of Australia where she discussed space science and research in a variety of venues including, but not limited to, Melbourne University, Victoria's State Parliament, Deakin University, and Scienceworks Planetarium Melbourne. Co-I Dava Newman delivered multiple talks this year, including the AWS Earth and Space Science Keynote Address.

3.2 SSERVI Seminar Series

FINESSE has supported the SSERVI Seminar Series for the duration of the FINESSE project. This is a virtual seminar series highlighting SSERVI science and related public programs and resources for the NASA Museum Alliance and Ambassadors, who share this content with their audiences around the country and the world. The FINESSE, RIS4E, DREAM2, and TREX SSERVI teams and NASA's Lunar Reconnaissance Orbiter (LRO) contributed,

Figure 8. Top left: PI Heldmann recording the "Gravity Assist" podcast with NASA Chief Scientist Jim Green. Top right: PI Heldmann serving on a panel discussion at the Metropolitan Museum of Art. Lower left: Deputy PI Lim speaking at the Scienceworks Museum in Australia. Lower right: a) Deputy PI Lim during a panel discussion at the Melbourne Museum. b) Co-I Dava Newman delivering the AWS Earth and Space Keynote Address.

adding to participation in previous years from the VORTICES and IMPACT SSERVI teams, as well as SSERVI Central.

3.3 Analogs Focus Group

In 2019 the SSERVI Analogs Focus Group was established by FINESSE PI Heldmann, FINESSE Deputy PI Lim, and RIS4E PI Glotch. Terrestrial analog field studies offer the unique opportunity to prepare for robotic and human planetary missions. Analogs provide the opportunity to conduct studies and tests related to science, mission operations, and technology in a relevant environment at relatively low cost and risk. The SSERVI Analogs Focus Group aims to bring together members of the community to discuss and review various aspects of fieldwork including, but not limited to, field sites, deployment logistics, field instrumentation, concepts of operations, software and hardware testing, etc. This Group currently hosts quarterly virtual seminars which are recorded and posted on the SSERVI website for later viewing. Deputy PI Lim gave the first seminar titled “Analog Field Campaign Management and Logistics,” PI Heldmann gave the second seminar titled “Terrestrial Analog Fieldwork: Overview of Science and Exploration Research to Enable Lunar and Planetary Exploration,” and Tim Glotch gave the third seminar titled “Field and Sample Analogs in Preparation for Future Human Exploration of the .” More information can be found on the SSERVI Analogs Focus Group website at https://sservi.nasa.gov/analogs-focus-group/.

4. Student / Early Career Participation

High School Students

1. Chanel Vidal, Iowa City West High School, field geology.

Undergraduate Students

1. Erin, Sandmeyer, Idaho State University, volcanics; tephrostratigraphy at Kings Bowl.
2. Allison, Trcka, Idaho State University, volcanics; tephrostratigraphy at Kings Bowl.
3. Caleb, Renner, Idaho State University, volcanics; remote sensing of lava types.
4. Trevor, Miller, Chico State University, volcanics; lava margins.
5. Omar, Draz, University of Western Ontario, impact cratering; breccias and melt rocks.
6. Bethany, Kersten, University of Idaho, volcanics, engineering.
7. Hailey, Johnson, University of Idaho, volcanics, instrumentation.
8. Avery, Brock, University of Idaho, volcanics; aerospace engineering.
9. Mareyna, Karlin, University of Idaho, volcanics; instrumentation.
10. Jonathan, Preheim, University of Idaho, volcanics; remote sensing.
11. William, Miller, University of Idaho, volcanics; technology.

Graduate Students

1. Hester, Mallonee, Idaho State University, volcanics; lava texture classification.
2. Gavin, Tolometti, University of Western Ontario, volcanics; petrographic texture and lava flow morphology.
3. Ethan, Schaeffer, University of Arizona, volcanics; fractal dimensions of lava margins.
4. Chris, Brown, Carleton University, volcanics; lava tubes.
5. Meghan, Fisher, Idaho State University, volcanics; explosive volcano eruptions.
6. Ali, Bramson, University of Arizona, volcanics; lava flow margins.
7. Sean, Peters, Arizona State University, volcanics; lava flow margins.
8. Mary, Kerrigan, University of Western Ontario, impacts; impact-generated hydrothermal systems.
9. Rebecca, Wilks, University of Western Ontario, impacts; impact melt veins.

10. Auriol, Rae, University of Western Ontario / Imperial College London, impacts; shock studies of central uplifts.

11. Audrey, Horne, Arizona State University, impacts; geochronology.

12. Anna, Brunner, Arizona State University, impacts; geochronology.

Postdoctoral Fellows

1. Alexander, Sehlke, NASA Ames Research Center, volcanics; lava flow morphology and physical properties of the flows, handheld field instrumentation (NASA Postdoctoral Program [NPP] position now complete).

2. Erika, Rader, NASA Ames Research Center, volcanics; spatter cone deposits (NASA Postdoctoral Program [NPP] position now complete).

3. Michael, Sori, University of Arizona, volcanics: lava flow margins.

4. Mark, Biren, Arizona State University, impacts; geochronology.

5. Cameron Mercer, NASA Goddard Space Flight Center, geochronology.

New Faculty Members

1. Catherine, Neish, University of Western Ontario, volcanics; radar mapping of lava flows.

2. Erika, Rader, Idaho State University, volcanics; spatter cone deposits.

3. Deepak, Dhingra, Indian Institute of Technology, Dept. of Earth Sciences, volcanics; remote sensing.

5. Mission Involvement

1. LCROSS, Anthony Colaprete, Project Scientist

2. LCROSS, Richard Elphic, Science Co-I

3. LCROSS, Jennifer Heldmann, Science Co-I, Observation Campaign Coordinator

4. VIPER, Anthony Colaprete, Project Scientist

5. VIPER, Richard Elphic, Deputy Project Scientist

6. VIPER, Jennifer Heldmann, Science Co-I

7. VIPER, Amanda Cook, Instrument Co-I

8. VIPER, Matthew Deans, Co-I

9. VIPER, Darlene Lim, Co-I

10. VIPER, Kris Zacny, Instrument Co-I

11. Lunar Reconnaissance Orbiter, Richard Elphic, Diviner imaging radiometer Co-I

12. Lunar Reconnaissance Orbiter, Catherine Neish, Co-I on Mini-RF

13. Lunar Reconnaissance Orbiter, Mike Zanetti, Science Team Member

14. Lunar Reconnaissance Orbiter, Alexandra Matiella Novak, Mini-RF Staff Scientist

15. Lunar Reconnaissance Orbiter, Andrea Jones, EPO Lead

16. OSIRIS REx, Chris Haberle, OTES Instrument Engineer

17. LADEE, Anthony Colaprete, PI

18. LADEE, Richard Elphic, Project Scientist

19. LUNA-H Map, Anthony Colaprete, Co-I

20. Lunar Flashlight, Barbara Cohen, PI

21. Dawn, Brent Garry, Vesta Participating Scientist Team

22. Dawn, Georgiana Kramer, Adjunct Science Team Member

23. ROSETTA, Georgiana Kramer, VIRTIS instrument

24. Chandrayaan-1, Georgiana Kramer, M3 instrument

25. Cassini, Steve Squyres, Imaging Team Co-I

26. Cassini, Catherine Neish, Associate Science Team Member

27. Mars Moon eXplorer (MMX – JAX, Richard Elphic, Co-I on MEGANE gamma ray and neutron spectrometer)

28. Korean Pathfinder Lunar Orbiter, Richard Elphic, Co-I on Korean gamma ray instrument

29. Korean Pathfinder Lunar Orbiter, Kyeong Kim, PI on gamma ray detector

30. Mars Odyssey, Chris Haberle, THEMIS Collaborator

31. Mars Odyssey, Suniti Karunatillake, Gamma and neutron spectrometer team

32. Mars Exploration Rovers, Steve Squyres, PI

33. Mars Exploration Rovers, Barbara Cohen, Associate PI

34. Mars Exploration Rovers, Livio Tornabene, Co-I

35. Mars Exploration Rovers, Sarah Stewart Johnson, Co-I

36. Mars Exploration Rovers, Suniti Karunatillake, Co-I

37. Mars Exploration Rovers, Kris Zacny, Instrument Co-I

38. Mars Science Laboratory (Curiosity rover), Barbara Cohen, Participating Scientist

39. Mars Science Laboratory (Curiosity rover), Chris McKay, Co-I

40. Mars Science Laboratory (Curiosity rover), Raymond Francis, Co-I

41. Mars Science Laboratory (Curiosity rover), Kris Zacny, Instrument Co-I

42. ExoMars Trace Gas Orbiter, Livio Tornabene, CASSIS (Colour & Stereo Surface Imaging System) Co-I

43. Mars Reconnaissance Orbiter, Steve Squyres, HiRISE Co-I

44. Mars Reconnaissance Orbiter, Livio Tornabene, HiRISE Co-I

45. Mars Reconnaissance Orbiter, Alexandra Matiella Novak, CRISM Mission Operations

46. Mars Express, Steve Squyres, Science Co-I

47. Mars 2020, Anthony Colaprete, Mastcam-Z Co-I

48. Orion spacecraft, Michael Downs, Test and recovery operations

49. Mars Icebreaker, Chris McKay, PI on proposed Discovery mission

50. Mars Icebreaker, Jennifer Heldmann, Co-I on proposed Discovery mission

51. Mars Icebreaker, Kris Zacny, Co-I on proposed Discovery mission

52. Dragonfly, Catherine Neish, Co-I on New Frontiers mission

53. ELSAH (Enceladus Life Signatures and Habitability), Chris McKay, PI for proposed New Frontiers mission

54. ELSAH (Enceladus Life Signatures and Habitability), Jennifer Heldmann, Science Team Co-I

55. Mars Express, Mike Zanetti, Science Team Member

56. ISS (International Space Station, mission scheduling software), Jessica Marquez, Playbook Co-I

6. FINESSE Awards (Year 6)

- Jennifer Heldmann, NASA / SSERVI Angioletta Coradini Mid-Career Award
- Darlene Lim, WINGS WorldQuest Women of Discovery Award – Air & Space
- Darlene Lim, Honoree / International Guest of Honor, Australia National Science Week
- Dava Newman, Elected to The Aerospace Corporation's Board of Trustees
- Andrea Jones, NASA Special Act Award issued by Science Leadership at GSFC in recognition for outstanding support of Apollo 50 activities
- Andrea Jones, NASA Group Achievement Award, LRO Public Engagement Team
- Andrea Jones, NASA Group Achievement Award, DREAM2 Center for Space Environments Science Team
- Linda Kobayashi, NASA Intelligent Systems Division Superior Accomplishment Spot Award for improving safety processes for field deployments
- Christopher Haberle, NASA Group Achievement Award for OSIRIS-REx Asteroid Approach and Preliminary Survey

- Christopher Haberle, OSIRIS-REx PI Award of Distinction (individual)
- Gordon Osinski, 2019 Earth Planetary Science, and Field Training Certificate of Appreciation, NASA Johnson Space Center for Astronaut Class training
- Steve Squyres, appointed Chief Scientist at Blue Origin
- Anthony Colaprete, CLPS PI, Near-Infrared Volatile Spectrometer **System (NIRVSS)**
- Richard Elphic, CLPS PI, Neutron Spectrometer System **(NSS)**
- Janine Captain, CLPS PI, Mass Spectrometer Observing Lunar Operations **(MSolo)**
- **Kris Zacny, CLPS, PlanetVac** for acquiring and transferring regolith from the lunar surface to instruments (for in situ analysis) or sample returned container (for sample return missions)
- Kris Zacny CLPS, LISTER (Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity)
- **Kyeong Kim, KPLO (Korea Pathfinder Lunar Orbiter) PI,** Gamma-Ray Spectrometer (KGRS)
- Barrett Caldwell, Purdue College of Engineering's Faculty Award of Excellence for Engagement and Service
- Shannon Kobs Nawotniak, Outstanding Researcher Faculty Award 2019, Idaho State University
- Shannon Kobs Nawotniak, appointed Honors Program Director, Idaho State University
- David Saint-Jacques, successful return from International Space Station (ISS) on June 24, 2019
- Dava Newman:
- Elected to the Aerospace Corporation Board of Trustees, 2020-
- Elected ISU Governing Member 2020-
- Co-Chair of the National Academies, Committee on Biological and Physical Sciences in Space, 2019-
- International Women's Day - Dr. Dava Newman Barbie space doll by Mattel™ 2019
- Phi Beta Kappa Academic Honor Society Visiting Scholar 2019
- Sea Space Symposium - Elected to Membership 2018
- 2018 Lowell Thomas Award - Explorers Club
- AIAA Jeffries Aerospace Medicine and Life Sciences Research Award, 2018
- Fellow of the American Institute of Aeronautics and Astronautics, 2018

Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT)

Mihaly Horanyi
University of Colorado, Boulder, CO

The dust accelerator facility (Fig.1) remains a unique facility to study hypervelocity (→→ 100 km/s) dust impacts for basic physics studies, and for the testing and calibration of flight instruments. We have served several NASA and ESA missions for damage studies, testing, and calibration, including NASA's Cassini, New Horizons, Solar Probe Plus, Europa Clipper, IMAP, and ESA's Destiny Plus missions. The facility is open to the US lunar, space and planetary sciences communities, and our international partners.

1. IMPACT Team Report

1.1 Dust Accelerator Projects

1.2 Small-Scale Laboratory Experiments

1.2.1 As a high-school physics project in IMPACT, plasma glow discharges were produced in air in a ~1-m-long glass vacuum tube under the pressure of 12–113 mTorr (Fig. 2). The full potential profiles throughout the glow discharge regions were characterized using a cold emissive probe with the current-bias method. Secondary electron emission from the probe determined the local plasma potential. The measured potential profiles showed good agreement with the theoretical expectations. A large potential drop was measured in the cathode dark space followed by a potential plateau through the negative glow

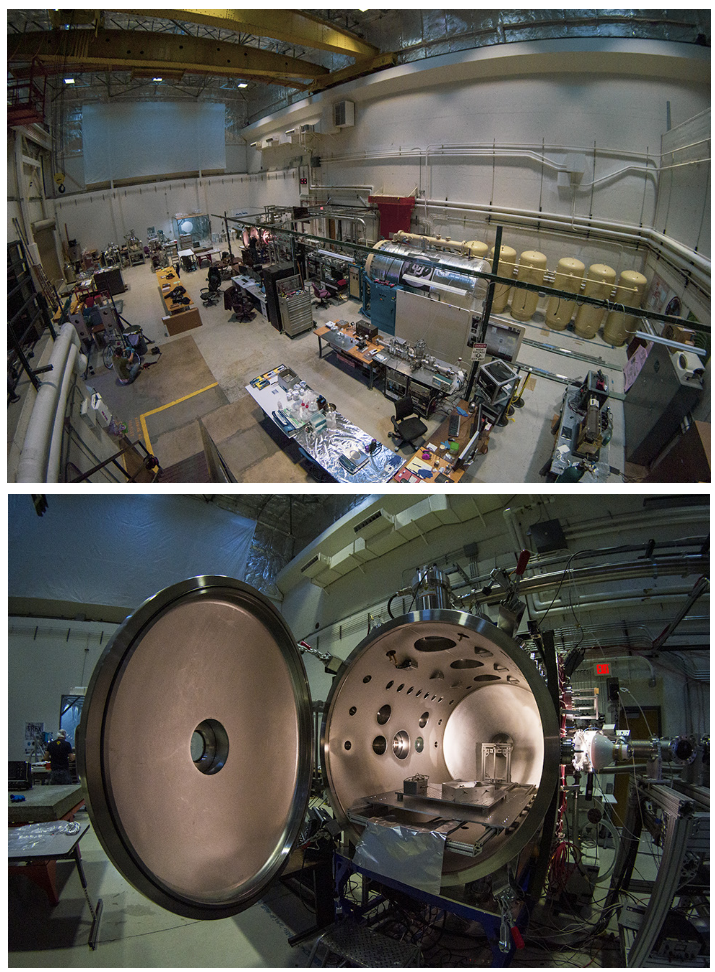
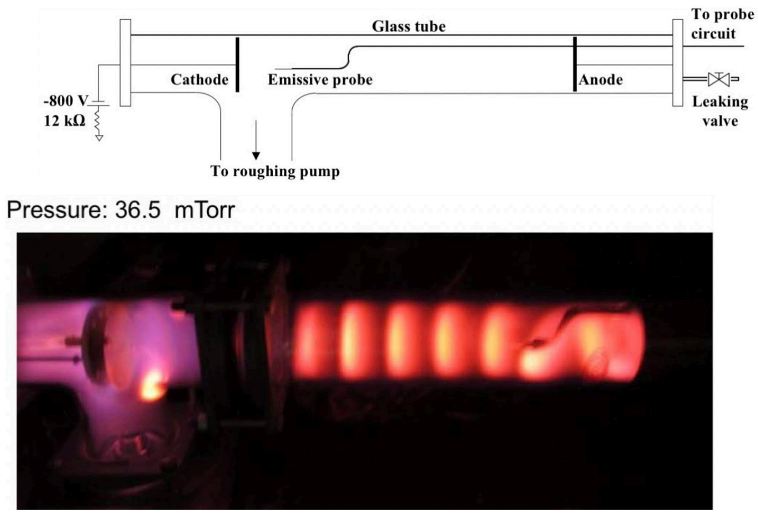


Figure 1. IMPACT continued to upgrade its dust accelerator facility (left) and its various target chambers. Our target options include a) a gas target for meteoroid ablation studies; b) a cryogenic target for ice impact experiments, and c) a large impact chamber that can accommodate experiments that need rotational and/or translational staging in the dust beam (right). In Y6, the Laboratory for Atmospheric and Space Physics (LASP) and the Department of Physics financed the construction of a new class 10,000 clean room for IMPACT to support its instrument development efforts for space flight.



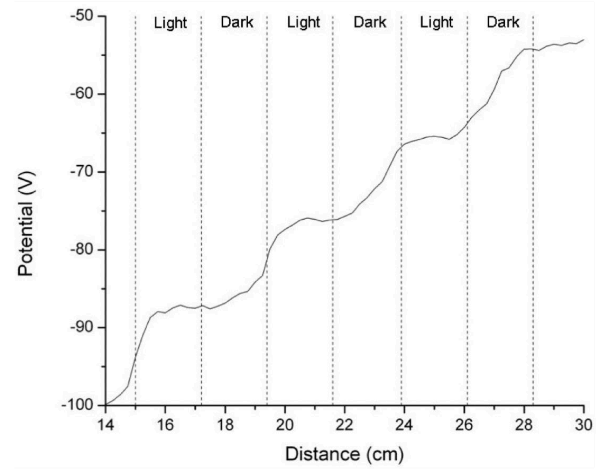


Figure 2. Schematic of the experimental apparatus (top left). Image of the plasma glow discharge with the pressure of 36.5 mtorr (bottom left). The measured potential characteristics (right) of the striations with an indication of the light/dark regions (Radisch et al., IEEE Trans. Plasma Sci., 2019).

and Faraday dark space regions. Striations in the positive column are shown as stair-step-like multiple potential double layers with potential steps close to the ionization energy. The project was led by two high school students and was summarized in a refereed publication (Radisch et al., *IEEE Trans. Plasma Sci.*, 2019).

1.2.2. Surface oxidation of Langmuir probes is an important issue for probe measurements in space environments. We examined this effect on photoemission from probe surfaces of various materials. Photoemission is either a contamination for traditional Langmuir probes or a necessity for electric field probes in low-density plasma. Our results show that all materials after oxidation have a varying degree of reduction in photoemission. The photoemission of copper, gold, and niobium drops most significantly followed by DAG213 (a resin-based graphite coating), TiN (titanium nitride), and rhenium. Iridium, DAG213, and AquaDAG (graphite coating) have the largest photoemission after oxidation, making them appropriate coating candidates for electric field probes. Overall, iridium is found to be a coating material appropriate for both electric field probes and Langmuir probes (Samaniego et al., *JGR*, 2018).

1.2.3. The surfaces of airless planetary bodies directly interact with the solar wind plasma and ultraviolet radiation, resulting in surface charging and formation of a sheath above the surface. These interactions are further complicated by the presence of craters with characteristic sizes spanning over orders of magnitude from centimeters to kilometers. We have presented laboratory results (Figure 3) to show that the plasma sheath formed in a crater varies significantly, depending on the radius of the crater compared to the Debye length of ambient plasma. When the Debye length is much smaller than the radius of the crater, the plasma expands into the crater and forms a sheath along the crater wall and floor. When the Debye length is comparable to or larger than the radius of the crater, the potential in the crater becomes more homogenous with a largely reduced

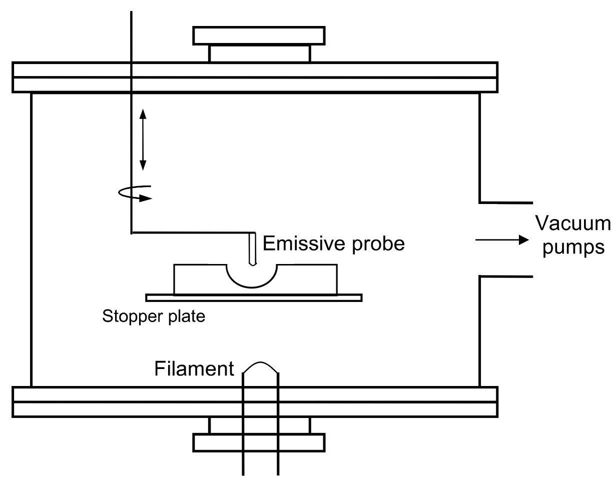
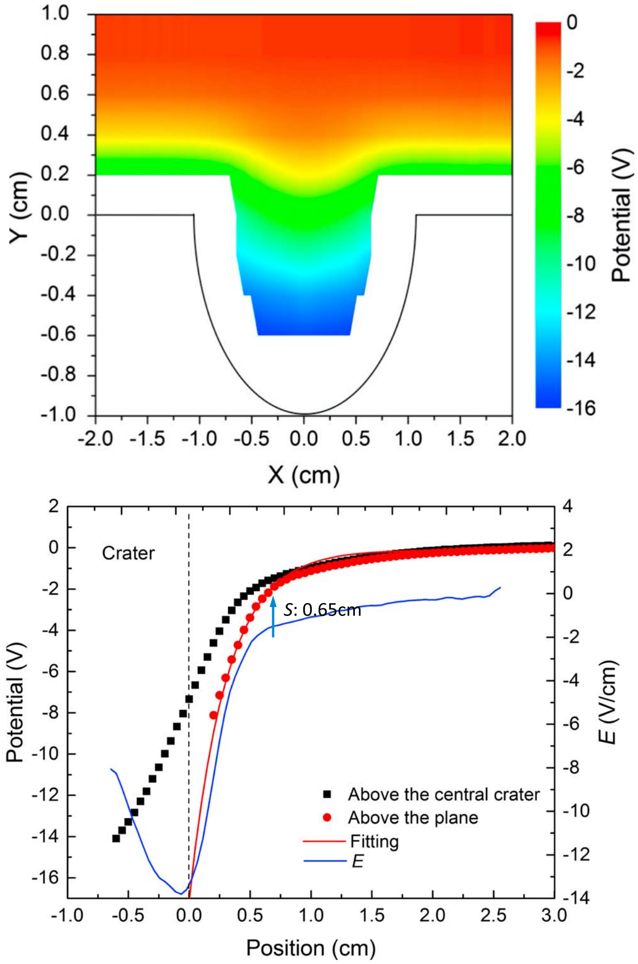


Figure 3. Schematic of the experimental setup (above). Potential profiles for a case where the crater radius R > S, the thickness of the plasma sheath. Potential contours at the crater (top, next page) and the vertical potential profiles along the axis of the center of the crater and above the plane surface (bottom, next page). The electric field (E) profile is the derivative of the potential profile along the axis of the central crater (Wang et al., *JGR*, 2019).



electric field. A double layer is formed between the crater and ambient plasma. It is likely that the electrons slowed down by the sheath cannot be efficiently reflected back to the plasma due to the reduced electric field and pile up within the crater, causing an increased electron density that crosses over the density of the ions (Wang *et al.*, *JGR*, 2019).

1.3 Data Analysis and Modeling

1.3.1 Earth's Moon is surrounded by an ever-present dust cloud produced by meteoroids impacting its surface. By measuring this dust cloud and comparing to computer simulations, we determined certain properties of the meteoroids producing it, such as size, mass, and speed. This information, in turn, is important for determining how protected a spacecraft needs to be to survive the journey through our solar system. To derive these meteoroid properties, however, we must first determine the average shape of the ejecta dust produced by one impact. Objects impacting a powdery surface typically emit a cone of dust upward. We have determined how wide and hollow this cone is on average by comparing measurements of the lunar dust cloud acquired by the Lunar Dust Experiment on-board NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) mission using a 3-D simulation of a meteoroid impacts. We found that the cone is far narrower than previously thought (Bernardoni *et al*., *GRL*, 2019; Pokorny *et al*., JGR, 2019). These results (Fig. 4) have been extended to predict observation by future lunar polar orbiting spacecraft (Szalay *et al*., *JGR*, 2019), and to other airless planetary objects, including 3200 Phaeton, the target of ESA's Destiny Plus mission, and were used to predict the dust impact rates during a flyby of asteroids (Szalay *et al*., *Planetary & Space. Sci.,* 2019; Cohen et al., *Meteoritics and Planetary Sci.*, 2019).

1.3.2 The Reiner Gamma swirl is a prime location to investigate lunar albedo patterns and their co-location with magnetic anomalies. The precise relationship between impinging plasma and the swirl, in particular how these interactions vary over the course of a lunar day, remain an open issue. We used a fully kinetic particle-in-cell

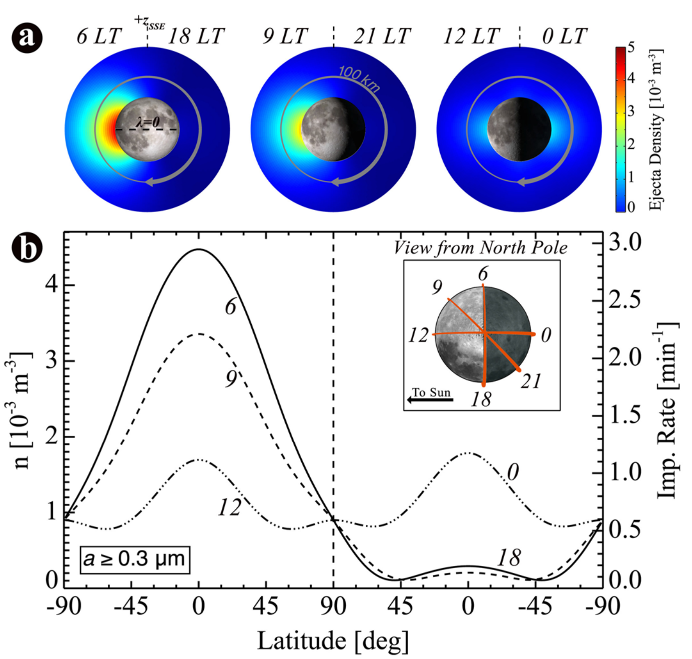


Figure 4. (a) Side view of the lunar dust densities for three planes perpendicular to the +z axis, up to 250-km altitude (not to scale). The location of the 100-km orbit is shown on each. (b) Local dust density and impact rate for an orbiting spacecraft as a function of latitude. The inset shows the three orbits in a view from the top. All quantities shown for a ≥ 0.3 μm (Szalay et al., *JGR*, 2019).

code, coupled with a magnetic field model based on in situ observations, and simulated the interaction with the Reiner Gamma anomaly for all plasma regimes the region is exposed to along a typical orbit, including different solar wind incidence angles and the Moon's crossing through the terrestrial magnetosphere. The energy flux profile matches all large-scale signatures of the albedo pattern only when integrating over the full lunar orbit. Including He^{2+} as a self-consistent plasma species is crucial to reproduce the correct brightness ratios between the inner and outer bright lobes, the dark lanes, and the mare background (Deca *et al*., *JGR*, 2019).

2. Inter-team/International Collaborations

CLASS Center for Lunar and Asteroid Surface Science (PI D. Britt): strong common interest in the possibility of Fe-catalyzed chemical reactions on asteroid surfaces which have been weathered by impacting micrometeorites.

DREAM (PI W. Farrell): longstanding successful collaboration on vapor and plasma release due to micrometeoroid impacts and plasma modeling.

IMPACT continued to serve as the 'center of gravity' for cosmic dust and dusty plasma research within SSERVI, and had complementary research projects with several of SSERVI teams and international partners:

NESS Network for Exploration and Space Science (PI J. Burns): collaboration supports efforts to minimize dust impact hazards for radio antennas, and assess solar wind charging effects on devices placed on exposed planetary surfaces.

REVEALS Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (PI: T. Orlando) common projects include dust charging, tribo- and impact-induced prebiotic chemistry, as well as a jointly mentored NPP Fellow (M.J. Schaible).

RISE2 Remote, In Situ, and Synchrotron Studies for Science and Exploration 2 (PI T. Glotch) ongoing projects on understanding the processes related to space weathering

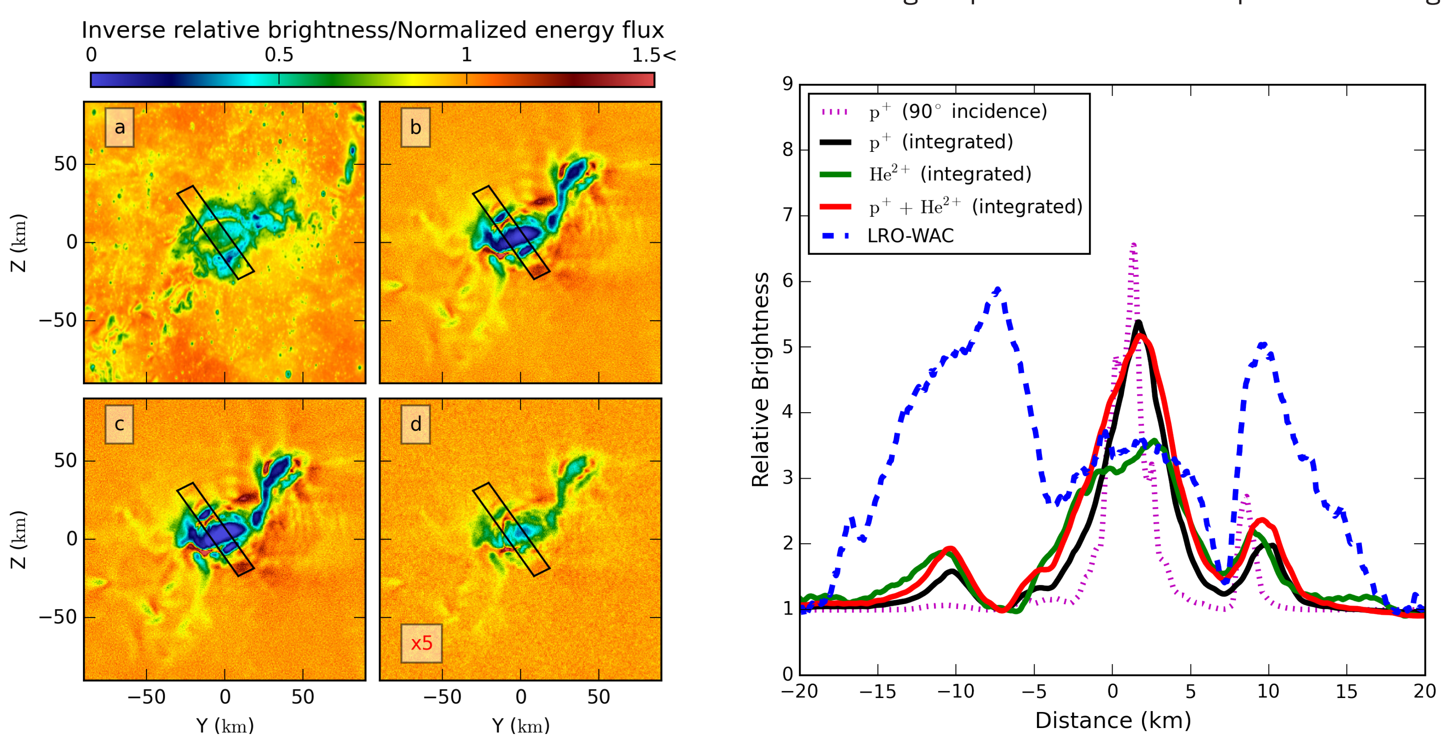


Figure 5. Comparison of the relative brightness of Reiner Gamma with the simulated energy flux to the surface, integrated over one lunar orbit. a) LRO-WAC image (a smaller number indicates a brighter surface area). b-d) Energy flux to the surface combining p^+ and He^{2+}, p^+, and He^{2+}, respectively. The He^{2+} fluxes have been enlarged five times. The black boxes indicate the part of the domain used to construct the right figure (Deca et al., *JGR*, 2019).

by systematically bombarding well-characterized minerals with high-speed dust particles.

TREX Toolbox for Research and Exploration (PI A. Hendrix) ongoing collaborations on laboratory efforts and working jointly on Public Engagement opportunities.

International Partners: IMPACT built active working relationships with its international partners from Germany, Canada, Norway, and Japan.

Germany: Long-term close collaborations exist between the Cosmic Dust Research Group at the University of Stuttgart, led by Prof. Ralf Srama. We have an active exchange program for students, postdocs and researchers. The University of Colorado and the University of Stuttgart signed a Memorandum of Understanding to set the framework for collaborations in lunar and space research. The proposed theoretical and experimental work on regolith characterization are continuing in collaboration with the dust group at the Technical University, Braunschweig, led by Prof. Jurgen Blum. Impact experiments involving mass spectroscopy are part of an ongoing collaboration with the group at the Free University of Berlin led by Prof. F. Postberg.

Canada: We have recently started common projects with the group at the University of Alberta, led by Prof. R. Marchand on modeling plasma surface interactions.

Norway: Ongoing collaborations with the group at the University of Oslo led by Prof. W. Miloch address new instrument ideas. We have been selected for 2018/9 funding by the Partnership Program with North America, Norway, that pays all travel and living expenses of IMPACT students visiting Oslo, and the Norwegian students visiting us.

Japan: We have been collaborating with the group at the Kobe University led by Prof. Y. Miyake on modeling of plasma-surface interactions to enable a better analysis and interpretation of existing observations and laboratory experiments at IMPACT.

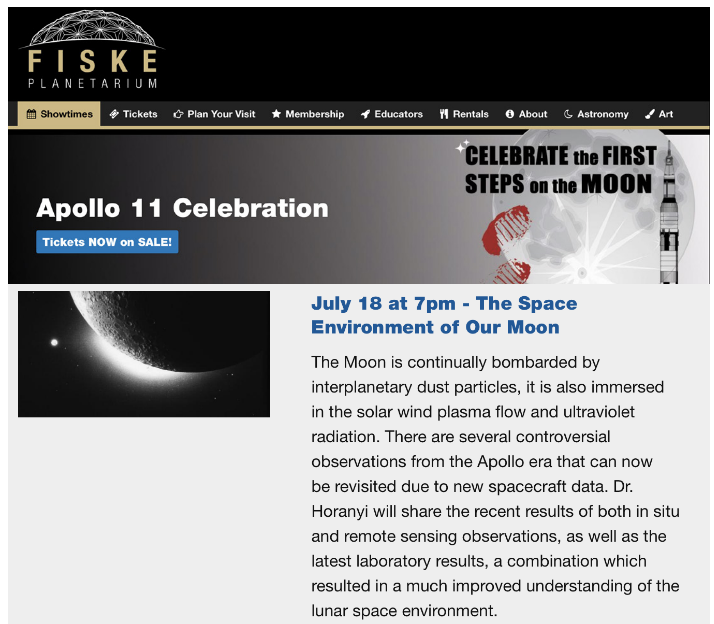
3. Public Engagement

3.1 Apollo 50th Anniversary

IMPACT participated in the Apollo 50th landing celebration lecture series organized by the CU's FISKE planetarium. M. Horanyi discussed our ongoing research and its relevance to returning humans to the Moon, and building permanent habitats. The audience represented a wide spectrum of interested visitors, ranging from students from our local elementary schools, to engineers and scientists from our local aerospace industry partners.

3.2 International Observe the Moon Night (InOMN) 2019

IMPACT participated in its 10th annual International Observe the Moon Night (InOMN) since 2010. During the evening of October 5th, IMPACT scientists and engineers engaged with hundreds of passersby on Boulder's Pearl Street mall sharing views of the Moon and answering questions about planetary science and exploration. An article in our local paper, the Daily Camera, reported on



this event

(https://www.dailycamera.com/2019/10/04/cu-boulders-lasp-hosting-to-showcase-moon-at-pearl-street-mall/).

3.3 Evaluation of IMPACT'S Y1-Y5 Public Engagement Activities

Dr. Susan Lynds (CIRES) completed a professional evaluation of our teacher workshop conducted in 2015 and our junior engineering student camps held in 2014, 2016, 2017, and 2018.

She concluded that the projects were successful in meeting all the goals and objectives. The full report is available upon request.

4. Student/ Early Career Participation

High-School Students

1. Madeleine Nagle (Boulder High School), Spectrometer control systems
2. Fiona Kopp (Boulder High School), Plasma glow discharge experiments

Undergraduate Students

1. Forrest Barnes, Control software development
2. Elizabeth Bernhardt, Accelerator experiments
3. Anthony Carroll, Dust dynamics in plasma
4. Alex Doner, Accelerator experiments
5. Benjamin Farr, Dust dynamics in plasma
6. John Fontanese, Accelerator experiments (promoted to Professional Research Assistant)
7. William Goode (graduated 2019), Accelerator diagnostic design (now a graduate student in IMPACT)
8. Noah Hood, Dust dynamics in plasma
9. Jack Hunsaker (graduated 2019), Impact plasma formation
10. Thomas Keaton, Dust dynamics in plasma
11. Zuni Levin, SIMION studies
12. Liam Merz-Hoffmeister, Impact charge measurements
13. Destry Monk, Accelerator control systems
14. Michael Nothem, Dust accelerator support
15. Alexandra Okeson (graduated 2019), Dust instrument software development
16. Joseph Schwan, Dust dynamics in plasma
17. Alexander Taylor (Grinnell College), Impact charge yield experiments

Graduate Students

1. Jared Atkinson (CO School of Mines), ISRU Experiments
2. Edwin Bernardoni, Plasma theory
3. Michael DeLuca, Micrometeoroid ablation experiments
4. Samuel Kočiščák (Charles University, Prague), Impact experiments on s/c antennas
5. Marcus Piquette, Surface/plasma interaction modeling
6. Joseph Samaniego, Langmuir probe measurements
7. Mitchell Shen, Impact experiments on s/c antennas
8. Zach Ulibarri, Ice target experiments

9. LiHsia Yeo, Solar wind experiments

Postdoctoral Fellows

1. Jan Deca, Computer simulations: plasma/surface interactions (Promoted to Research Scientist II)

5. Mission Involvement and Concepts

New instrument concepts are based on our laboratory experiments, and year-long senior aerospace engineering classes, achieving a Technical Readiness Level (TRL) of 3 using SSERVI support. These instrument concepts were proposed and have been selected for further technology development:

Double Hemispherical Probe (DHP): initially funded by SSERVI, now transitioned to NASA's Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program (PI: X. Wang).

Electrostatic Lunar Dust Analyzer (ELDA): initially developed by SSERVI support, now funded by NASA's Development and Advancement of Lunar Instrumentation (DALI) program (PI: X. Wang).

IMPACT involvement in missions:

JAXA's **Destiny Plus** mission to asteroid Phaeton will carry the **Destiny Dust Analyzer (DDA)** with M. Horanyi, S. Kempf, and Z, Sternovsky as co-investigators. IMPACT will continue supporting DDA by testing and calibration experiments at the dust accelerator facility.

NASA's **Europa Clipper** flagship mission will carry the **Surface Dust Analyzer (SUDA)** instrument, that was developed, and is currently being tested and calibrated at the dust accelerator facility. IMPACT investigators involved are S. Kempf (PI), M. Horanyi and Z. Sternovsky (CoI).

NASA's **Interstellar Mapping and Acceleration Probe (IMAP)** will carry the **Interstellar Dust Experiment (IDEX)** that is being developed, tested, and calibrated at the dust accelerator facility. IMPACT investigators involved are M. Horanyi (PI), Z. Sternovsky and S. Kemp (CoI).

6. Awards

Bill Goode (Aerospace engineering graduate student) received a second-place poster award at the 2019 NASA Exploration Science Forum. The award recognizes and rewards promising scientists while motivating and encouraging future work.

Institute for the Science of Exploration Targets (ISET)

William Bottke
Southwest Research Institute, Boulder, CO

1. ISET Team Report

1.1 Theme 1. Formation of the Terrestrial Planets and Asteroid Belt

1.1.1 Planetesimals to Terrestrial Planets: Collisional Evolution Amidst a Dissipating Gas Disk

The accretion and fragmentation code LIPAD was used to track growth from planetesimals to planets, examining how collisional grinding affects the final relative mass between Earth and Mars. For the combinations of disk mass, initial planetesimal radius, and gas disk lifetime explored in this work, we find the entire disk never reaches a simple bi-modal mass distribution. Instead, inside-out growth is amplified by the combined effects of collisional evolution of solid bodies and interactions with a dissipating gas disk. This leads to oligarchic growth never being achieved in different places of the disk at the same time. The planetesimal population is efficiently depleted in the inner disk where embryo growth primarily advances in the presence of a significant gas disk. Further out in the disk growth is slower relative to the gas disk dissipation, resulting in more excited planetesimals at the same stage of growth and less efficient accretion. This same effect drives mass loss due to collisional grinding, strongly altering the surface density of the accreted planets relative to the initial mass distribution. This effect decreases the Mars-to-Earth mass ratios compared to previous works with no collisional grinding. These simulations produce a first generation of planetary embryos that are stable for 10-20 Myr before having an instability and entering the chaotic growth stage. **(Walsh and Levison, Icarus, Volume 329, p. 88-100.)**

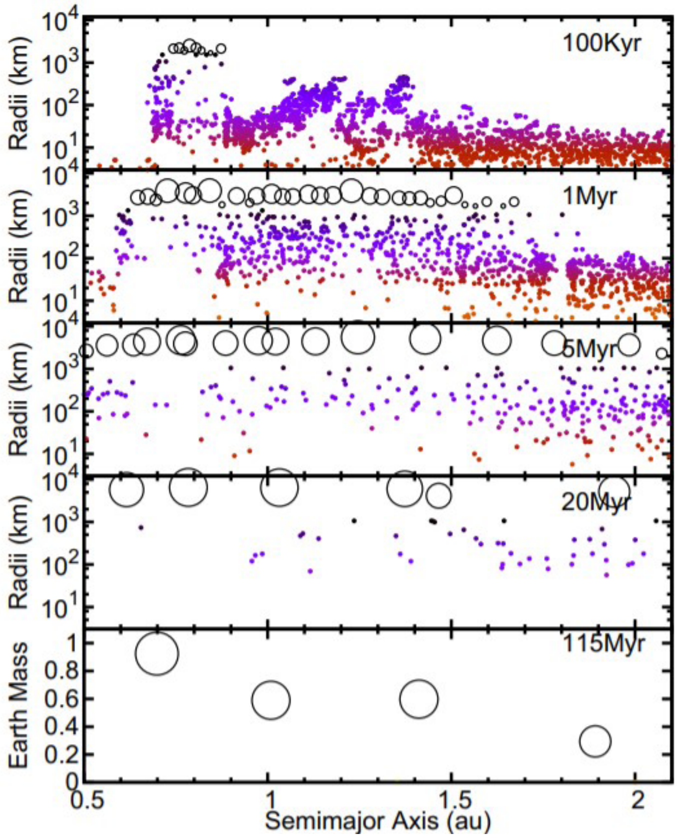


Fig. 1. The distribution of particle sizes at 100 kyr, 1 Myr, 5 Myr and 20 Myr, plotted as a function of Radius (km) versus semimajor axis (au). The bottom frame shows the mass of the final bodies in the system plotted as a function of semimajor axis.

1.1.1 Energy Dissipation in Large Collisions—No Change in Planet Formation Outcomes

It is often asserted that more accurate treatment of large collisions in planet formation simulations will lead to vastly different results—in particular a lower final angular momentum deficit (AMD—commonly used to measure orbital excitement). As nearly all simulations to date consider perfect merging (100% energy dissipation) during embryo-embryo collisions, and typically end up with an overexcited final terrestrial planetary system, it has been suggested that a better treatment of energy dissipation during large collisions could decrease the final dynamical excitation (or AMD). Although some work related to energy dissipation has been done (mostly during the runaway growth phase when planetesimals grow into protoplanets), this had never been fully tested in the post-runaway phase, where protoplanets (embryos) grow chaotically into planets via large collisions among themselves. Here we tested varying amounts of energy dissipation within embryo-embryo collisions. Our results show that varying the level of energy dissipated within embryo-embryo collisions does not play any important role in the final terrestrial planetary system. (**Deienno, R., Walsh, K. J., Kretke, K. A., Levison, H. F. 2019. Astrophysical Journal 876, 103).**

1.1.3 Collisional Evolution of Meter-to-Kilometer Sized Planetesimals in Mean Motion Resonances: Implications for Inward Planet Shepherding

Small particles (meter-to-kilometer-sized) can drift inwards through a protoplanetary disk due to their interaction with a gaseous nebula. If planets exist, these particles can get captured in mean motion resonance (MMR) and, if massive, exchange angular momentum with the planets. We studied the capture mechanism and collisional evolution of a swarm of massive inward drifting particles in MMRs with planets. Our results show that if massive particles are assumed to be rocky, collisions make the swarm of particles decrease in size. In this case, as their gas drag properties change (smaller particles drift faster through the gas nebula) they eventually leave the MMR. We conclude that, although some angular momentum exchange may exist, in no cases studied did the massive inward drifting particles significantly change the orbit of the planet. **(Deienno, R., Walsh, K. J., Levison, H. F. , Kretke, K. A. 2020. Astrophysical Journal, in press).**

1.2 Theme 2. Origin of the Earth-Moon and Phobos-Deimos

1.2.1 Lunar Accretion from Impact-generated Material

We developed a new model, HydroSyMBA, which combines a hydrocode inner disk model with an *N*-body accretion code. This is the first model capable of accurately tracking both the radial evolution of interior disk and the dynamics of lunar accretion beyond the Roche limit. We also explored the evolution of moons created in multiple impacts as they interact and collide, including effects on compositional heterogeneities in the resulting Moon. **Salmon & Canup (2019); Rufu & Aharonson (2019)**

1.2.2 Formation of the Moon from a Giant Impact with Earth

We gave the opening invited talk at the Apollo 50th anniversary science session at the 2019 LPSC, and are leading and co-authoring an extensive chapter on lunar origin to appear in New Views of the Moon II volume. We wrote an invited piece on lunar origin for a special issue of Astronomy (**Canup 2019a, 2019b; Canup et al. 2020**).

1.2.3 Evection Resonance in the Earth-Moon System

We used novel analytical and numerical models to assess how the evection resonance with the Sun would have affected the Earth-Moon system's angular momentum (AM). We find a range of evolution histories, which include those consistent with proposed "high-angular momentum" impact models for only a quite limited range of parameters (see Fig. 2). We presented talks at the June meeting of the Division of Dynamical Astronomy and the September joint DPS/EPSC meeting on this work, and

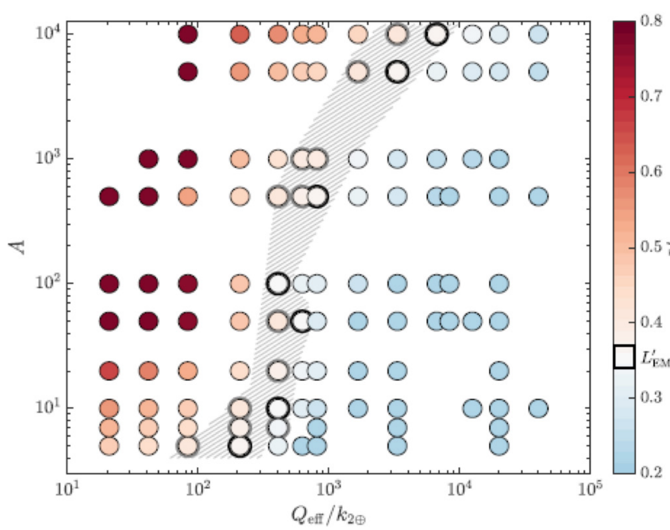


Fig. 2. Earth-Moon angular momentum (LF) after interaction with evection resonance, as a function of the initial terrestrial tidal dissipation factor and Love number, Qeff/k2E, for different values of the relative strength of tides in the Moon vs. the Earth (A). Grey region shows final AM values consistent with current Earth-Moon, accounting for AM change due to late accretion and solar tides. From Rufu & Canup (2020).

have submitted 2 papers to JGR Planets. (**Ward et al. 2020; Rufu and Canup 2020**).

1.2.4 Effect of Late Bombardment on Mars' Mantle Composition

We explored how the impact of large, differentiated projectiles onto early Mars could lead to isotopic in homogeneities in Pt and W consistent with those observed in martian meteorites. Such impacts are implied by the occurrence of the Moon forming giant impact, the formation of Phobos-Deimos via an impact, and the relative abundance on highly siderophile elements on the Earth vs. the Moon. **(Marchi, Walker, Canup, Science Advances, Feb 12, 2020).**

1.3 Theme 3. Solar System Bombardment

1.3.1 The Role of Impacts on Archean Tectonics

Marchi and Bottke worked in collaboration with C. O'Neill (Macquarie University, Australia) about the effects of collisions on early Earth. In this work, we developed numerical simulations of global tectonism with impacting effects, and simulated the evolution of these models throughout the Archaean for given impact fluxes. We demonstrated that moderate-size (~70 km diameter) impactors are capable of initiating short-lived subduction, and that the system response is sensitive to impactor size, proximity to other impacts, and also lithospheric thickness gradients. The results were published in Geology (O'Neill, C., Marchi, S., Bottke, W., and Fu, R., 2020, Geology, v. 48, https://doi.org/10.1130/ G46533.1)

1.3.2 Search for the H Chondrite Parent Body Among the Three Largest S-type Asteroids

Linking meteorites to source regions in the main asteroid belt is important for understanding the conditions under which their parent bodies formed. Ordinary chondrites are the most abundant class of meteorites on Earth, totaling 86% of all collected samples. Here we investigated the surface composition of three large S-type asteroids, (3) Juno, (7) Iris, and (25) Phocaea, using their near-infrared spectra (0.7-2.55 **μm**) to identify the parent body of the H chondrites. We used a Bayesian inference model to confirm the meteorite analogs of the three asteroids. Based on our Bayes classifier, we favor (3) Juno; it has the spectral properties similar to H chondrites, though its family is unlikely to produce sizeable H-chondrite-type near-Earth objects (NEOs). If Juno is the primary source of H chondrite meteorites, it suggests that an additional source is needed to explain the H-chondrite-type NEOs. **(Noonan, Reddy, Harris, Bottke, et al. 2019, AJ).**

1.3.3 A Possible Second Large Subglacial Impact Crater in Northwest Greenland

Following the discovery of the Hiawatha impact crater beneath the northwest margin of the Greenland Ice Sheet, we explored satellite and aerogeophysical data in search of additional such craters. Here we report the discovery of a possible second subglacial impact crater that is 36.5-km wide and 183 km southeast of the Hiawatha impact crater. Although buried by 2 km of ice, the structure's rim induces a conspicuously circular surface expression, it possesses a central uplift, and it causes a negative gravity anomaly. The existence of two closely spaced and similarly sized complex craters raises the possibility that they formed during related impact events. However, the second structure's morphology is shallower, its overlying ice is conformal and older, and such an event can be explained by chance. We conclude that the identified structure is very likely an impact crater, but it is unlikely to be a twin of the Hiawatha impact crater. **(MacGregor, Bottke, et al. 2019, GRL).**

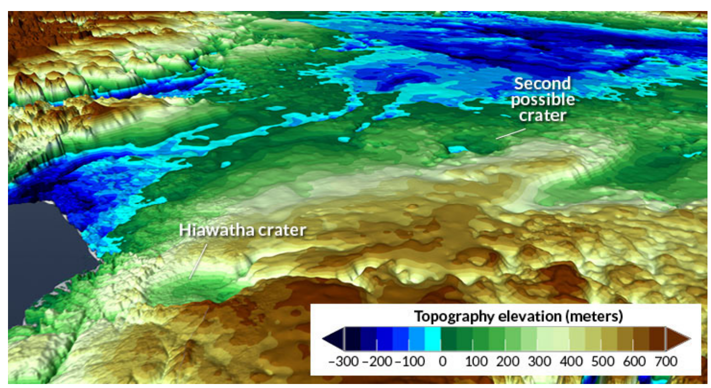


Fig. 3. A potential second crater carved into land that sits beneath Greenland's ice, as seen in this visualization, is just 183 kilometers away from Hiawatha, a large craterlike depression described in November.

1.3.4 Modeling the Chronologies and Size Distributions of Ceres and Vesta Craters

We infer the crater chronologies of Ceres and Vesta from a self-consistent dynamical model of asteroid impactors. The model accounts for planetary migration/instability early in the Solar System history and tracks asteroid orbits over 4.6 Gy. The model provides the number of asteroid impacts on different worlds at any time throughout the Solar System history. We combine the results with an impactor-crater scaling relationship to determine the crater distribution of Ceres and Vesta and compare these theoretical predictions with observations. We find that: (i) The Ceres and Vesta chronologies are expected to significantly differ from the lunar chronology, whereas the Ceres and Vesta chronologies are similar. (ii) The model results match the number and size distribution of large (diameter >90 km) craters observed on Vesta, but overestimate the number of large craters on Ceres. This implies that large crater erasure, probably due to the viscous relaxation of surface, is required for Ceres. (**Roig and Nesvorny 2020, AJ, in press**)

1.3.5 Non-Constant Impact Flux for the Earth-Moon System

We have determined the formation ages of 42 lunar craters with diameter ≥ 50 km originally categorized as Copernican or Eratosthenian using the densities of small craters superposed on their floors. These ages are used to explore if recent lunar bombardment by large asteroids (impactor diameter > 2-5 km) in the last 3 billion years has not been constant, but could be characterized by spikes or lulls, assuming that bombardment by the small asteroids (impactor diameter << 1 km) is constant. Impactors ~4 km appear consistent with the constant flux, while smaller impactors (~2-3 km) have probable spikes at ~2.2 (lasting 100-300 Myrs) and from 0.1-0.8 Ga with a lull in between, and larger impactors (~5-10 km) appear to have an overall reduced flux for the last 3 Ga. Peer reviews have been received and the manuscript is in moderate revision. **(Kirchoff, M.R., Marchi, S., Bottke, W.F., Chapman, C.R., Enke, B., 2020. Icarus, in revision).**

1.4 Theme 4. Properties and Populations of NEAs

1.4.1 Overview of Physical and Dynamical Evolution of NEAs

The CU team led by Dan Scheeres has continued its research on the effects and implications of non-gravitational forces and weak cohesive bonds within primitive Solar System bodies. Over the last year 7 papers were published or accepted that were supported, in part,

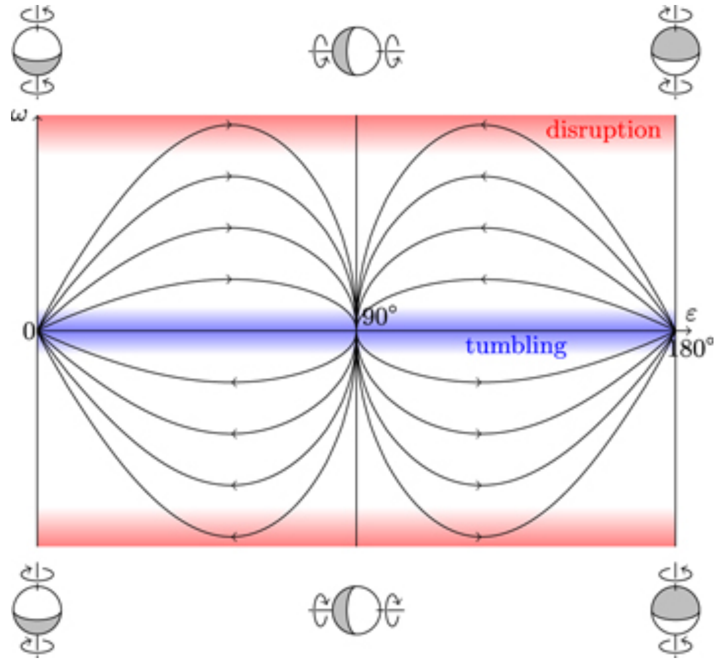


Fig. 4. Qualitative map of YORP dynamics, accounting for the most common combination of YORP obliquity and spin rate coefficients. Asteroids are predicted to migrate between equilibrium states at 0, 90 and 180 degrees of obliquity, reaching their maximum spin rates at obliquities away from these points.

by the ISET institute. These included papers that studied the granular mechanics of rubble pile bodies when cohesion is present, papers that have probed deeper into the expected dynamical evolution of small bodies under the effect of non-gravitational forces, and specific studies of near-Earth asteroids and their dynamics when subject to close flybys. In the area of cohesive rubble pile asteroids we had several published results. This includes analysis of failure modes of cohesive surface regolith for fast rotating asteroids, fundamental constraints for when asteroid pairs and clusters can occur, and contributions to a wide-ranging review article on rubble pile asteroids. In the topic of non-gravitational effects on asteroid spin states, we published an article that predicts the presence of equilibrium states under the YORP effect, meaning that small asteroids can evolve to spin obliquities and spin rates where the YORP effect is "turned off" and the spin state can remain fixed for long durations. This is an important finding; if verified, it would change our conception of how asteroid spin rates evolve in the main belt and NEO populations. In the area of asteroid dynamics, we contributed to a detailed analysis of the flyby of asteroid Duende by the Earth, providing clear reconstructions of its spin state and evidence for the degree to which its close passage caused the asteroid to enter a tumbling mode. This work has involved support from senior research scientist Paul Sanchez, post-doc Alex Golubov, and PhD student Conor Benson. **(C. Benson, D.J. Scheeres and N. Moskovitz. 2020; Icarus, in press; Moskovitz, Benson, Scheeres et al. 2020. Icarus, in press; Sanchez and Scheeres 2020, Icarus, in press. Scheeres 2020, Celestial Mechanics and Dynamical Astronomy 132:4; Hestroffer, P. Sanchez 2020, Astron. Astrophys. Review, in press; Pravec et al. 2019; Icarus 333: 429-463; Golubov and Scheeres. 2019. Astrophysical Journal 157(3): 105.)**

2. Inter-team/International Collaborations

- Robin Canup co-led an Origin of the Earth-Moon Systems chapter with K. Righter, a member of the CLSE team (Canup et al. 2020)
- Simone Marchi and Robin Canup collaborated with Richard Walker of the CLSE team on constraining the early bombardment of Mars. Results are in press at Science Advances (Marchi et al. 2020)
- In collaboration with Craig O'Neill of the SSERVI Australia team, Bottke/Marchi investigated the long term effects (e.g. volcanism) of early collisions on the Archean/Hadean Earth
- Bottke and Marchi interact with L. Elkins-Tanton (SEEED) on a number of early planetary formation and bombardment projects, most prominently the Psyche mission. Elkins-Tanton is the PI of that mission
- Marchi was the organizer of Main Belt Gateway conference partially sponsored by our SSERVI node: http://www.iaps.inaf.it/sz/mainbelt2019/
- Bottke has interacted with a wide range of international scientists over the past year, the main ones being: David Vokrouhlicky (Charles U., Prague, Czech Republic), Alessandro Morbidelli (Observartorie de la Cote d'Azur, Nice, France), Rebecca Ghent/Sara Mazrouei (U. Toronto, Canada), and Tom Gernon (Ocean and Earth Science, University of Southampton, Southampton, UK). The combined work has covered a wide variety of collisional, dynamical, and cratering projects
- Scheeres is a member of the ISET, IMPACT and CLASS SSERVI teams to study the mechanics of cohesive asteroid regolith. As such, he participates with these teams:
- Scheeres and Sanchez have collaborated with the STRATA-I space station experiment with support of the CLASS SSERVI team

3. Public Engagement Report

Summer Science Program (SSP) Our collaboration with SSP continues to be a success. Kretke, Salmon, Kirchoff, and a new participant, Rufu, served as science instructors for the 36 high-school students each in New Mexico and Colorado in July, 2019. ISET members guided the students through a SSERVI-rich participatory experience using the numerical integrator Swift to integrate the orbits of their observed asteroids into the future. The students then analyzed and presented their results on the fate of their asteroid to their peers. This was the first opportunity many of these high-school students have had to participate in a scientific presentation. We also provided scientific lectures to the students on asteroid populations and their dynamical evolutions, including chaos theory.

The students at both campuses completed surveys about their experiences with the ISET research project. 92% of the students either agreed or strongly agreed that participating in the research project helped them understand how computer modeling is applied to science. In addition, 75% agreed or strongly agreed that

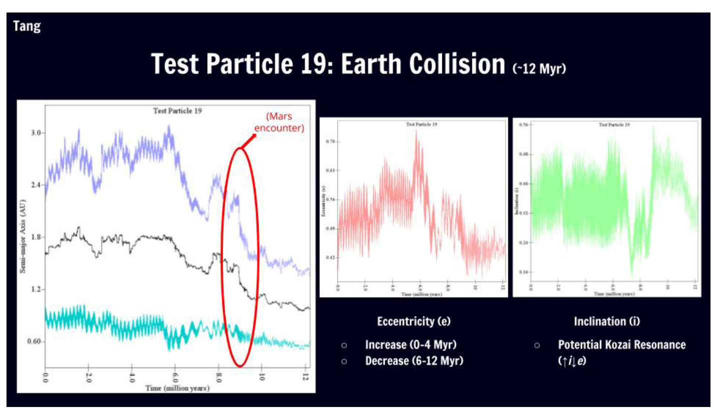
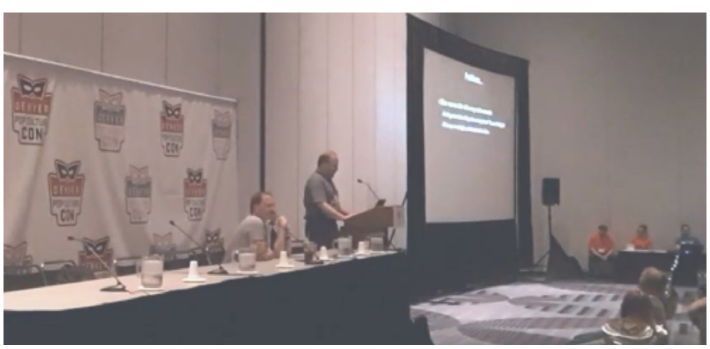


Fig. 5. An example results slide from a team presentation.

the discussions and interactions with ISET scientists were valuable. We think these two student comments summed up the experience best: “Learning yet another way for computers to be applied to astronomy. These two subjects go so much better together than I had first thought!” and “I think it was cool to see the future of our asteroid and learn about the interconnectedness of the Solar System and the way bodies affect each other.”

Denver Pop Culture Con

For the past few years ISET scientists have participated in the Denver Pop Culture Con (previously Denver Comic Con) presenting SSERVI science and exploration to public audiences ranging in age from preschoolers to adults. This year was no exception. We also continued our partnership with the Lucy mission through K. Kretke as the lead of the Communications, Public Outreach and Workforce development for the Lucy Mission. She teamed up with Kirchoff to design and present an activity for elementary children on “Exploring the Smallest Members of Our Solar System.” For this activity, children first learned about the variety of small bodies in our Solar System and how we are exploring them both with missions and occultations. Then they built their own small bodies out of clay to get a hands-on feel for the different shapes and ponder how those shapes came to be. We ended with handing out spacecraft paper models for the kids to take home. Bottke and several others also gave talks on exploring the Moon, asteroids, upcoming NASA missions, and so on. An example of one of their talks can be found at: https://www.youtube.com/watch?v=zgaIUAVNJYM



Bill Bottke and other SwRI scientists presenting at Denver Pop Culture Con 2019.

Sharing Results

Bottke, Nesvorný, and Marchi all also gave public presentations to a variety of audiences. Kirchoff, Kretke, and Salmon participated in the Boulder Planetary Scientists events at the Longmont Farmer’s Markets, bringing planetary science to the general public.

4. Student/Early Career Participation

Postdoctorate Fellows

- Raluca Rufu (post-doc at SwRI as of 8/18)

Dr. Rufu is working with Canup on a variety of projects, including the evection resonance and modeling giant impacts (Ward et al. 2020; Rufu and Canup 2020).

- Oleksiy Golubov, University of Colorado, Aerospace Engineering

Dr. Golubov has had yearly visits to CU from the Ukraine, where he is a junior faculty member. During his visits he works with Prof. Dan Scheeres on the effect of solar radiation on the dynamical evolution of small asteroids.

- Masatoshi Hirabayashi, University of Colorado, Aerospace Engineering

Dr. Hirabayashi was initially supported by the SSERVI grant to perform stress and failure analysis of asteroids using commercial and custom continuum mechanics models. He subsequently had a post-doc position with Dr. Jay Melosh at Purdue University. In the last year he has started as an Assistant Professor of Aerospace Engineering at Auburn University.

Graduate Students

- Shota Takahashi, University of Colorado, Aerospace Engineering

Takahashi was supported as a PhD student in the final year of the SSERVI grant. His focus was on the exploration dynamics of spacecraft in the vicinity of small bodies, with applications to both exploration activities and to taking scientific measurements of small bodies. He will graduate in 2-3 years.

- Stefaan Van wal, University of Colorado, Aerospace Engineering

Van wal was supported as a PhD student by the SSERVI grant. His focus is on the dynamics of motion on the surfaces of small bodies, with applications to both exploration activities and to geophysical processes on small bodies. He has graduated and carried out a post-doc working with the Hayabusa2 mission.

- Travis Gabriel, University of Colorado, Aerospace Engineering

Gabriel performed research at CU under the SSERVI grant focused on the energetics of stable configurations of rubble pile asteroids. He finalized his Master's degree at CU in 2016, published his research in a journal paper and has now transitioned into the PhD program at Arizona State University where he is working with Dr. Erik Asphaug.

5. Mission Involvement

1. Lucy, Hal Levison, Principal InvestigatorHal

Levison is the PI of the mission Lucy that will perform a tour of Jupiter's Trojan Asteroids. The mission was selected for phase B in January 2017. Launch is scheduled for 2021.

2. Lucy, Julien Salmon, Sequencing

Salmon has been assisting PI Levison in designing encounters of each of the mission's targets, demonstrating that the mission scientific requirements could be achieved. He helped design sequences of observations that would provide the necessary spatial coverage and minimum resolution with each of the instruments.

3. OSIRIS-REx, Kevin Walsh, Regolith Development Working Group, Lead Scientist

Kevin Walsh is a Co-I on NASA's asteroid sample return mission OSIRIS-REx. He is the lead scientist for the Regolith Development Working Group, whose responsibilities include mapping the global geology of the asteroid Bennu, helping to select the sample-site, and interpreting the outcome of the Spacecraft-Asteroid interaction.

4. OSIRIS-REx, William Bottke, Dynamical Evolution Working Group, Lead Scientist

Bottke is a Co-I on NASA's asteroid sample return mission OSIRIS-REx. He is the lead scientist for the Dynamical Evolution Working Group, whose responsibilities include understanding the collisional and dynamical evolution of the asteroid Bennu and measuring the Yarkovsky and YORP effects on this body.

5. Psyche, William Bottke, Co-I on the Science Team

Bottke is a Co-Is on NASA's Psyche mission, a planned orbiter mission that will explore the origin of planetary cores by studying the metallic asteroid 16 Psyche. His job will be to understand the origin, dynamical, and collisional evolution of Psyche.

6. Lucy, William Bottke, Co-I on the Science Team

Bottke is Co-I on NASA's Lucy mission, the first space mission to study Jupiter's Trojan asteroids. His role will be to understand the origin, dynamical, and collisional evolution of the Trojan asteroids observed by the spacecraft.

7. NEO Surveyor, William Bottke, Co-I on the Science Team

Bottke is Co-I on NASA's Near-Earth Object Surveyor mission (formally NEOCam). It is designed to discover and characterize most of the potentially hazardous asteroids that are near the Earth. His role will be to understand the origin, dynamical, and collisional evolution of the NEOs and main belt asteroids observed by the survey. This mission is in extended Phase A, with its fate not yet determined.

8. Dawn, Simone Marchi, Co-I on the Science Team

Marchi is a Co-I on NASA's Dawn mission to Vesta and Ceres. He has mainly contributed to the characterization of cratering histories of Vesta and Ceres, as well as their surface compositions, and geological evolutions.

9. Rosetta, Simone Marchi, Associate Scientist on the OSIRIS camera

Marchi is an Associate Scientist to ESA Rosetta's OSIRIS camera system Science Team. He has conducted geomorphological studies of comet 67P and pursued how these studies could inform the origin of 67P.

10. Lucy, Simone Marchi, Deputy Project Scientist (DPS)

Marchi is DPS of NASA's Lucy mission to Jupiter's Trojan asteroids. Marchi contributes over a wide range of activities, including the definition of the mission's science goals, instrument performance, observation planning etc.

11. Psyche, Simone Marchi, Relative Ages Working Group, Lead Scientist

Marchi is a Co-I on NASA's Psyche mission, a planned orbiter mission that will explore the origin of planetary cores by studying the metallic asteroid 16 Psyche. Marchi's role will be to understand the collisional evolution of Psyche, and map craters on Psyche.

12. JUICE, Simone Marchi, Associate Scientist on the JANUS camera system Science Team

Marchi is an Associate Scientist on ESA JUICE Janus camera system. JUICE will study Jupiter, Ganymede, Europa and Callisto. His role is to characterize the cratering histories of the Galilean satellites.

13. BepiColombo, Simone Marchi, Co-I on the Science Team

Marchi is a Co-I on ESA's BepiColombo SIMBIOSYS stereo camera. BepiColombo will study Mercury. His role is to provide cratering model ages and support to geomorphological investigations.

14. OSIRIS-REx, Daniel Scheeres, Radio Science Working Group lead

Scheeres is a Co-I on NASA's asteroid sample return mission OSIRIS-REx. He is the lead scientist for the Radio Science Working Group, whose responsibilities include estimating the mass and gravity field of the target asteroid Bennu, measuring the Yarkovsky and YORP accelerations for that body, and using this information to constrain and analyze the geophysics of the asteroid.

15. Hayabusa2, Daniel Scheeres, Interdisciplinary Science Team Co-I

Scheeres is a Co-I on the Interdisciplinary Science team of the Japanese Hayabusa2 mission to asteroid Ryugu. He will contribute his expertise to the analysis of that asteroid's dynamical environment, and through a collaboration with the OSIRIS-REx team will analyze the tracking data in order to constrain the asteroid's mass.

16. Janus, Daniel Scheeres, PI

Scheeres is a PI of one of NASA's Small Innovative Mission for Planetary Exploration (SIMPLEx) finalists. Janus is designed to fly by two binary asteroids, or asteroids orbiting a common center of mass, to image the system using both visible and infrared cameras. These small satellites will launch in 2022 to reach the asteroid system in 2026.

6. Awards

In 2019, Raluca Rufu was awarded the Weizmann Institute of Science National Postdoctoral Award.

Remote, In Situ, and Synchrotron Studies for Science and Exploration (RIS^4E)

Timothy Glotch
Stony Brook University

1. RIS^4E Team Report

The RIS^4E team is organized into four distinct themes, which in addition to our Public Engagement efforts, form the core of our science and exploration efforts. Results from the no cost extension sixth year of RIS^4E activities for each of the four themes are discussed below.

1.1 Theme 1. Preparation for Exploration: Enabling Quantitative Remote Geochemical Analysis of Airless Bodies

During the sixth year of RIS^4E activities, the Theme 1 team continued the development of models designed to enable more quantitative interpretation of infrared spectral data of airless bodies. These models (1) enable a more detailed understanding of the effects of space weathering on the visible/near-infrared (VNIR) spectral properties of airless bodies, (2) pave the way for radiative transfer-based thermal infrared (TIR) spectroscopic analysis of the Moon and Mars, and (3) provide a new way to classify telescopic spectra of near-Earth asteroids. They are described below.

1.1.1 Test of Effective Medium Theory to Model Space Weathered Particles

Building off our previous work in developing a hybrid T-matrix/radiative transfer model for thermal-IR spectroscopic applications, we have extended our modeling efforts to VNIR wavelengths, with a focus on better understanding the effects of nanophase metallic Fe size and abundance on the spectra of space weathered materials. The effects of space weathering on visible/near-IR spectra are commonly modeled using Hapke theory, along with a combination of Mie theory and effective medium theory (EMT) to calculate the scattering and absorption behavior of host particles and nanophase opaques. Former Stony Brook graduate student Carey Legett and PI Glotch conducted a direct test of this method by using the EMT/Mie/Hapke approach and a T-matrix/Hapke approach that allows a more physically realistic model of the scattering particles. Direct comparisons of the methods (Figure 1.1) for the single host-particle cases shows large differences between the EMT/Mie/Hapke method and

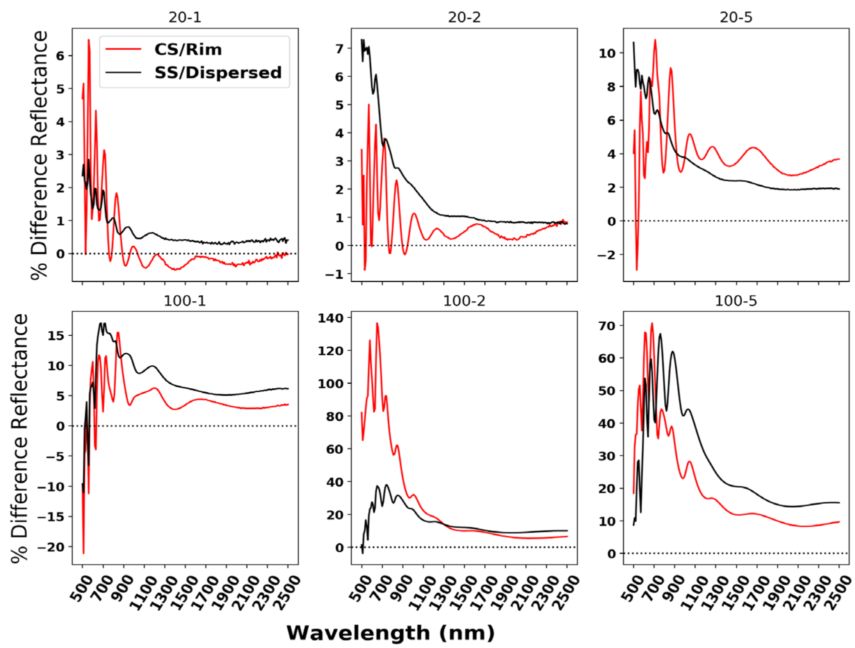


Figure 1.1. Model cases showing the % difference in calculated reflectance between a space weathered particle with average optical properties calculated by effective medium theory and a space weathered particle with scattering properties explicitly modeled using the Multiple Sphere T-Matrix code. The red curves show the results for coated sphere cases and the black curves show the results for single sphere cases. The top row includes models for an olivine host particle with 20 nm 0Fe particles making up 1, 2, and 5 wt.% of the particle. The bottom row includes models for an olivine host particle with 100 nm ^{0}Fe particles making up 1, 2, and 5 wt.% of the particle.

the more physically realistic T-matrix/Hapke method, especially at short wavelengths and high Fe abundances. Caution should be used in interpreting the results of such models. When computational resources allow, direct calculation of the scattering properties using physically realistic geometries is highly preferred over the effective medium theory technique.

1.1.2 Calculation of TIR Optical Constants for the Triclinic Mineral Labradorite

Stony Brook graduate student Cheng Ye has completed a model of the 3 TIR principal indices of refraction (optical constants) of labradorite, a triclinic plagioclase feldspar mineral (Figure 1.2). Optical constants are critical input parameters in radiative transfer theory, which enable modeling of spectra for the extraction of mineral abundances and grain sizes from a remotely sensed spectrum. TIR optical constants of most triclinic rock-forming minerals are not available due to the complexity associated with the derivation of optical constants of low-symmetry minerals. The calculation required measurement of 12 total TIR reflectance spectra—4 spectra at different orientations on 3 mutually orthogonal cut faces of a large single crystal. Subsequent to the spectral measurements, Ye used a Lorentz-Lorenz dispersion model to simultaneously fit all 12 spectra and calculate the refractive indices. **This is the first calculation of its type for a geologically important triclinic mineral and the calculated refractive indices will aid in quantitative radiative transfer-based analyses of TIR data sets of planetary surfaces. The publication of this work represents the culmination of roughly a decade of model development, optimization, and spectral measurements.** Former RIS4E students Jessica Arnold and Melinda Rucks (now postdoctoral researchers at Carnegie Institute and Princeton, respectively) also contributed to this work.

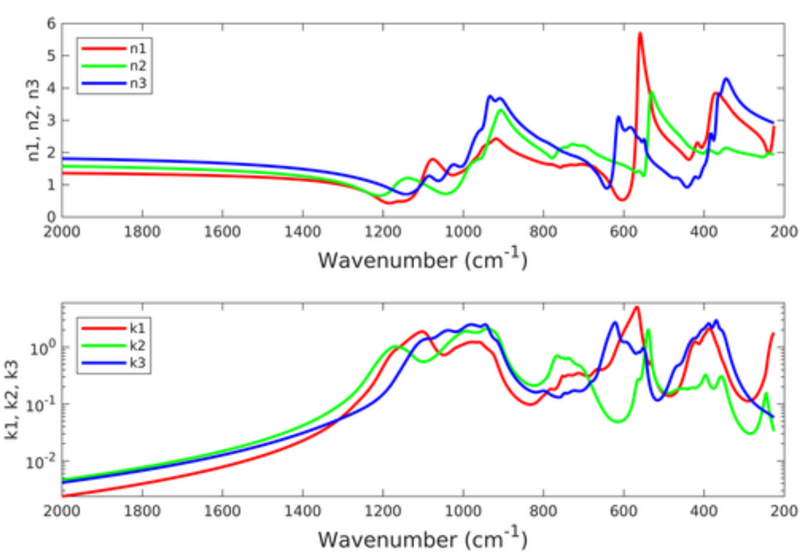


Figure 1.2. The three principal complex refractive indices calculated for labradorite. Top (n, real component of the refractive index). Bottom (k, imaginary component of the refractive index).

1.1.3 Quantitative Machine-Learning Based Modern Taxonomy for Asteroids

Harvey Mudd College undergraduate student Sydney Wallace, working with Co-I's Burbine and Dyar at Mount Holyoke College, has begun the development of an automated machine-learning based taxonomic classification method for asteroids based on the infrared spectra of a wide variety of meteorites with known compositions. Several asteroid classification systems based on visible and infrared spectroscopy have been developed over the years, most recently culminating in the Bus-DeMeo (BDM) taxonomy, which uses slope scores and principal component analysis of reflectance spectra to group similar objects together. However, this method is still challenging to use, requiring that many objects (~40%) be classified visually. For this work, Wallace began the process of creating a new machine-learning based taxonomy for asteroids based on correspondences between laboratory spectra of meteorites with known classes and asteroid data. The model uses 1623 meteorite spectra and was tested on 694 asteroid spectra. The most successful classification algorithm we tested was the Gaussian Kernel Support Vector Machine (SVM) method. This method applied to baseline-corrected spectra, reproduced the BDM classifications 78% of the time. When trained on the meteorite spectra, the SVM classification method can be used to apply mineralogical classes to asteroid spectra (Figure 1.3). Ultimately, results should enable direct mineralogical linkages between meteorites and their parent bodies, and provide an understanding of the distribution and abundances of objects with varying compositions throughout our Solar System.

1.2 Theme 2. Maximizing Exploration

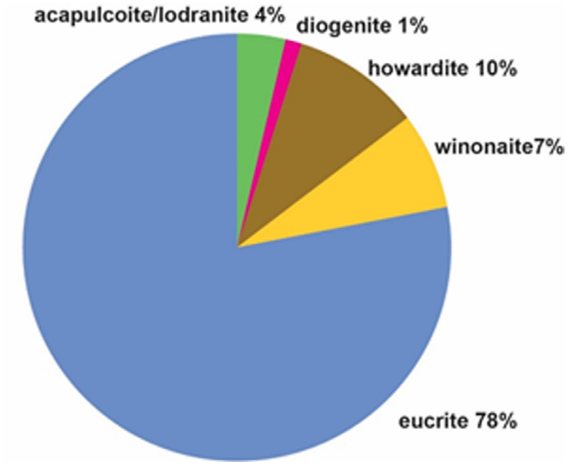


Figure 1.3 Percentages of V-type asteroids assigned to each meteorite group using the SVM after the AirPLS baseline removal method was applied.

Opportunities: Development of Field Methods for Human Exploration

The RIS[4]E team did not conduct field work during the no cost extension period in Year 6. However, the Theme 2 team did continue to work on projects related to previous field work, and took part in NASA and Canadian Space Agency planning activities for future human and rover operations on the Moon.

1.2.1 CSA Lunar Analog Field Work

Co-I Cloutis (U. Winnipeg) completed a 2-week deployment in the Canary Islands as part of a CSA-funded lunar exploration rover program. His team conducted rover-like field work using reflectance, Raman, and LIBS spectroscopies to identify targets of interest based on imagery collected in the field and transmitted back to mission control in London, Ontario. The field sites were lunar mare analogues in Lanzarote, Canary Islands and consisted of fresh basalts erupted in 1730-1736. The team's goals were to see how best to use a rover and the associated instruments to characterize these basalts for ilmenite (opaque) concentrations, evidence of hydration, and discrimination of different geological units.

1.2.2 A LiDAR Investigation of Pyroclastic Surge Cross-Beds, Kilbourne Hole, NM, USA

Co-I Whelley (NASA Goddard) leads a team that is studying the emplacement of units at the Kilbourne Hole maar crater in the Potrillo Volcanic Field in New Mexico. The objectives of the work are to characterize Kilbourne Hole using a portable terrestrial laser scanner (TLS) instrument and to constrain the number of explosive volcanic eruptions that led to the formation of the crater, and whether the maar crater formation was the result of one or a few major explosions, or incremental growth through a series of smaller eruptions. Maar craters form as the result of interaction between a magma body and water in the subsurface. A maar crater formed by a few major explosions suggests the presence of a discrete magma body, which is exhausted or disrupted after the explosion. The incremental growth model suggests that both the magma and aquifer recharge between explosions and that the crater and tuff (ash)-ring geometry are constructed over a span of activity.

Whelley and his team collected data from 22 scan positions covering 800 meters of the SE rim of the tuff ring (e.g., Figure 1.4). From these data they were able to make 17 cross-bedding foreset attitude measurements and constrain the nature of the eruptions. They conclude that the dip directions of the beds shift over the length of their measurements, suggesting a counter-clockwise migration of the eruption center. This, in turn, suggests that Kilbourne hole was formed through incremental growth by migrating explosions.

1.3 Theme 3. Protecting Our Explorers: Understanding How Planetary Surface Environments Impact Human Health

The Theme 3 team worked to develop assay techniques designed to assess the identity and concentration of

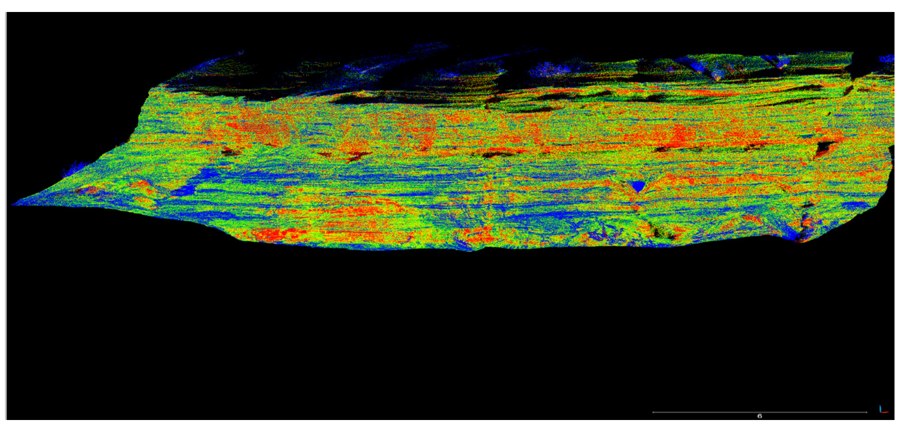


Figure 1.4 A subset of TLS surge-bed observations. Color is infrared (LiDAR) reflectance (blue is low, red is high).

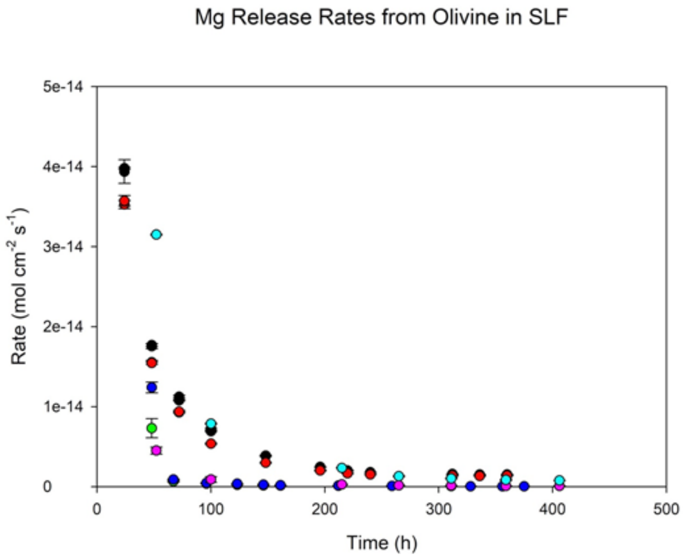


Figure 1.5 Olivine dissolution rates for fine particles (<10 μm) in simulated lung fluid at 37 °C.

reactive oxygen species (ROS) produced by interactions between lunar regolith simulants pulverized in the laboratory and various liquid media. In addition, they correlated the reactivity of lunar regolith simulants (measured by production of ROS) with toxicity as measured by cell death counts and DNA damage assays. The team also made the first attempts to quantify the differences in reactivity and toxicity between fresh and experimentally space weathered lunar regolith simulants.

1.3.1 Slow Reactivity of Olivine in Simulated Lung Fluid

Stony Brook graduate student Donald Hendrix and Co-I Joel Hurowitz conducted olivine ((Fe,Mg)2SiO4) dissolution experiments in simulated lung fluid at human body temperature (37 °C) to determine the rates of dissolution. They also conducted experiments in strong acid to check their methods against previous results. These experiments yielded rates consistent with literature rate estimates, indicating that the experimental methods are sound. Experiments conducted in the presence of simulated lung fluid (Figure 1.5) indicate that dissolution rates are orders of magnitude slower than those conducted in strong acid. These results imply that the lifetime of olivine particles in the human lung cannot be reliably estimated using published rates of dissolution. We will use the rate data from this study to determine the expected lifetime of respirable (<10 μm) olivine particles in the presence of lung fluid.

1.3.2 Macrophages Display Altered Cell Morphology and Uptake of Lunar Simulants

Stony Brook graduate student Kaitlyn Koenig and Co-I Stella Tsirka investigated the effects of several lunar simulants on macrophage cell cultures. Koenig and Tsirka exposed RAW264.7 macrophages to a suspension of lunar simulants in cell culture media. They acquired phase contrast images (Figure 1.6) with a Leica Sp8x confocal microscope. 3D renderings (bottom panel) show particulates within the cells, except in anatase-exposed macrophages. For these experiments, anatase (TiO_2) is known to be non-reactive with the cells. The simulant exposure experiment results indicate that the macrophages are being activated to different degrees by the simulants. The macrophages recognize the simulants as foreign objects and respond by trying to minimize the damage by enveloping and dissolving the simulant particles. However, if the damage caused by the simulants is too high, the cells become “proinflammatory” and release cytokines that cause cell death. In the human body, this can lead to respiratory problems over long periods of time.

1.4 Theme 4. Maximizing Science from Returned

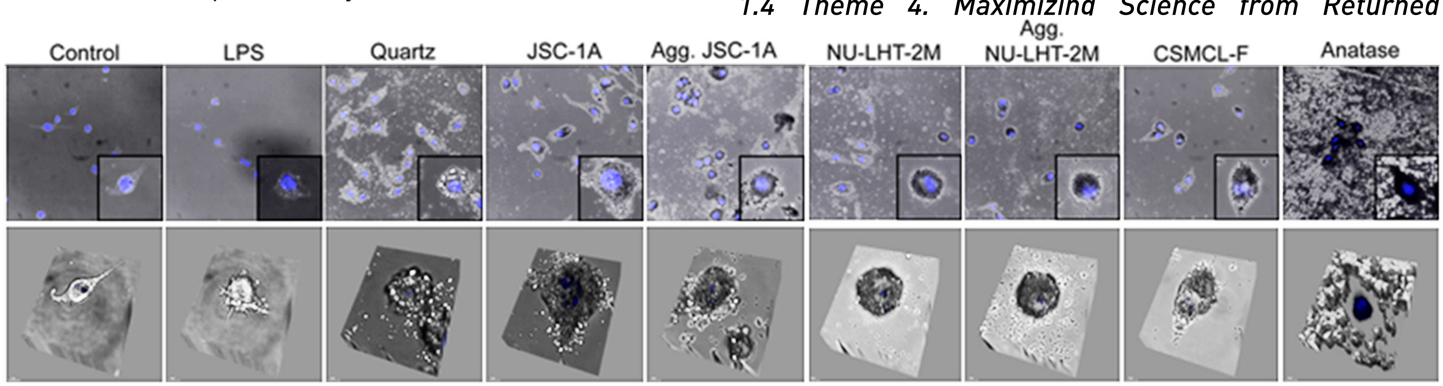


Figure 1.6 Macrophages interacting with lunar soil simulants. Top row includes photomicrographs of exposed macrophages. Cell nuclei are shown in blue. The bottom row shows 3D renderings of the macrophage-particle interactions.

Samples: Advanced Synchrotron and STEM Analysis of Lunar and Primitive Materials

Theme 4 team further developed the synchrotron nano-IR imaging and spectroscopy techniques for analysis of meteorites and, eventually, returned samples. Co-I's Darby Dyar and Kate Burgess were chosen to lead two teams selected to analyze previously unopened Apollo samples. Burgess and her team will use transmission electron microscopy of frozen samples and samples stored in helium to better understand the effects of space weathering on the surface of the Moon. Dyar and her team will use synchrotron X-ray absorption spectroscopy to examine the oxidation states of pyroclastic glass beads in vacuum-sealed and helium-stored samples, providing new insight into lunar volcanic processes.

1.4.1 Nano-IR Imaging and Spectroscopy of Minerals and Extraterrestrial Materials

In May of 2019, Glotch, Co-I Rhonda Stroud, and SBU graduate student Jordan Young spent 3 days at the Synchrotron Infrared Nanospectroscopy (SINS) beamline at the Advanced Light Source at Lawrence Berkeley National Lab. They collected near-field infrared (nano-IR) spectra on oriented silicate mineral standards, ordinary chondrites, and interplanetary dust particles. They also tested the ability to conduct nano-IR analyses on focused ion beam (FIB) sections attached to copper pegs. These analyses proved to be very difficult due to the geometry of the atomic force microscope (AFM) cantilever portion of the instrument relative to the sample and copper peg holding it. Co-I Stroud will prepare additional FIB samples with different types of holders that are appropriate for both TEM and nano-IR measurements. We hope to examine these samples at an upcoming beamtime in 2020.

The team successfully collected nano-IR imagery and spectra from a thin section of the ordinary H5 chondrite ALH 77012. Young had previously used Raman spectroscopy to identify enclaves of polycyclic aromatic hydrocarbons (PAHs) within the meteorite. The degree of crystalline order of the PAHs provides a measure of the peak metamorphic temperature experienced by the meteorite's parent body. Nano-IR imagery acquired at a wavelength of ~6 μm (Figure 1.7) reveals differences in the phase and amplitude of the sample in a boundary region between a PAH-bearing surface and a silicate mineral. Spectra acquired on different regions of the surface indicate the presence of enstatite, an orthopyroxene phase, and a non-silicate mineral that likely hosts the carbon. Future investigations are planned to further characterize the carbon-bearing surfaces in several ordinary and carbonaceous chondrites. Infrared spectroscopy has the capability to provide a greater level of detail on the molecular structure of the carbon-bearing phases, and at more than an order of magnitude finer spatial resolution, than Raman spectroscopy alone.

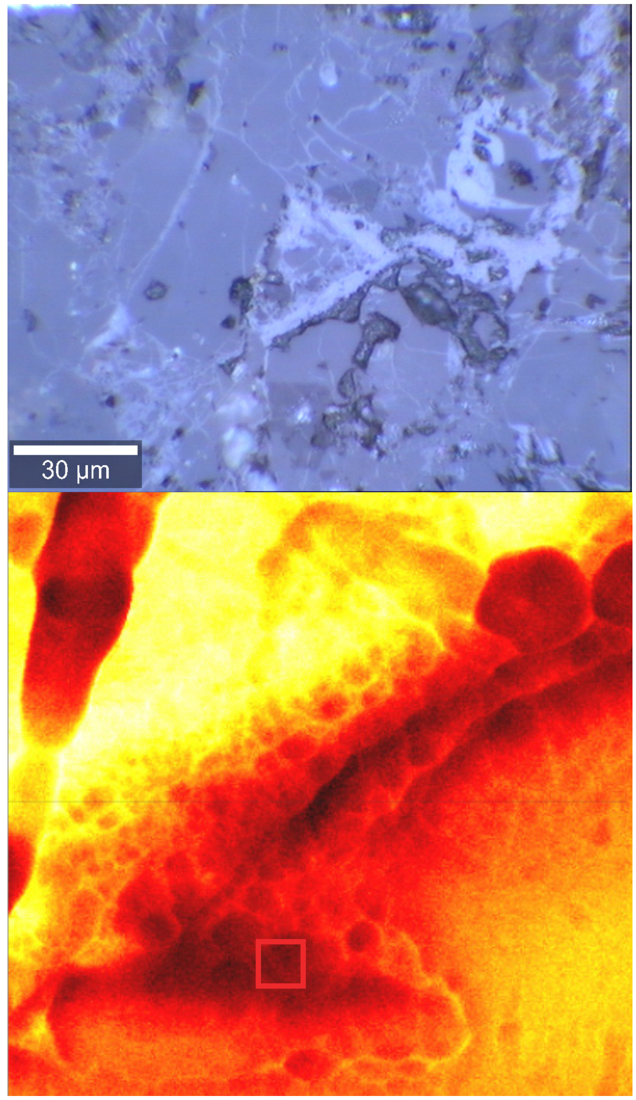


Figure 1.7 (Top) White lite photomicrograph of ALH 77012. The red outline shows the position of the IR image. (Bottom) Nano-IR image (~50 nm/pixel) displaying contrast differences between silicate (red) and non-silicate (yellow) surfaces.

2. Inter-team/International Collaborations

The RIS^{4}E team is dedicated to the concept of inter-team collaboration within the overall structure of SSERVI. Our Experiences have provided evidence that the whole of SSERVI is greater than the sum of its parts.

2.1 Inter-team Collaborations

2.1.1 Collaboration with the SEEED Team

Glotch and Jack Mustard from the SEEED team collaborated on the chapter "Theory of Reflectance and Emittance Spectroscopy of Geologic Materials in the Visible and Infrared Regions" in the book *Remote Compositional Analysis* published in 2019 by Cambridge University Press.

2.1.2 Collaboration with FINESSE Team

Glotch worked with Jennifer Heldmann and Darlene Lim to create the SSERVI Analogs Focus group. This group now has over 100 members on its email distribution list. It hosts focus group meetings at the annual NASA Exploration Science Forum and, with the support of SSERVI Central's technical staff, runs quarterly seminars related to analog activities. These seminars are recorded and available for playback by any member of the public or scientific community.

2.1.3 Collaboration with ESPRESSO Team

SBU graduate student Cheng Ye accompanied the ESPRESSO team on their field trip to the Pallisades Sill in New Jersey. Ye operated a portable ASD FieldSpec3 Max visible/near-IR spectrometer and acquired spectra of both fresh and weathered surfaces on the sill. These spectral data will be correlated with laser induced breakdown spectroscopy (LIBS), Raman, and other data from the sill acquired by the ESPRESSO team.

2.2 International Collaborations

Dr. Ed Cloutis (University of Winnipeg) is a RIS^{4}E collaborator and a Canadian Lunar Research Network (CLRN) team member, providing a link between the two teams. In each of the six years of our SSERVI collaboration, he has hosted a U.S. undergraduate student as a SSERVI summer research fellow. In the summer of 2019, he conducted rover-based lunar field analog work in the Canary Islands. Glotch served as a collaborator on the successful proposal to the Canadian Space Agency for that field work.

Dr. Neil Bowles (University of Oxford) is a RIS^{4}E collaborator, providing a link to the UK and broader European Solar System science and exploration communities.

Former RIS^{4}E postdoctoral researcher Dr. Mehmet Yesiltas is now a professor at Kirklareli University in his home country of Turkey. He is now a RIS^{4}E collaborator, working with PI Glotch and SBU graduate student Jordan Young on Raman spectroscopic measurements of ordinary and carbonaceous chondrites. He is a co-author on a paper by Young currently in review Meteoritics & Planetary Science, and a lead author on a paper with Young and Glotch that is soon to be submitted to a special issue of American Mineralogist focused on carbon in Earth and planetary materials. Co-I De Gregorio is serving as a guest editor for that issue. In December, 2019 he traveled for the second year in a row to the Princess Elizabeth Antarctic Station (operated by Belgium). He is leading a team of Turkish scientists on an expedition to search for meteorites on the blue ice sheets near the research station.

3. Public Engagement

The RIS^{4}E team continued to support public engagement through the activities noted below.

3.1 Social Media

As a joint effort, multiple team members help to keep the public informed of RIS^{4}E science and exploration activities going on throughout the year over several social media platforms, including Twitter (@RIS4E_SSERVI) and Facebook (RIS4E Science and Exploration.) Updates from the lab, field, outreach events, and the exciting science happening throughout the RIS^{4}E team are shared with the general public in short, digestible bursts in order to excite the public about RIS^{4}E science and exploration. A highlight this year was public reporting on the final RIS^{4}E field season to the Potrillo Volcanic Field in New Mexico.

3.2 Public Events

The RIS^{4}E team supported public engagement at many events, including talks, interviews and hands-on activities.

Co-I Patrick Whelley traveled to Death Valley to teach tourists about maar craters. He taught them about water-magma interactions that cause explosive eruptions and how to “read the pyroclastic layers” along the rim of Ubehebe crater. Understanding styles and consequences of these and other explosive eruptions helps us identify and interpret pyroclastic deposits on the Moon and other bodies and is a major focus of RISE2 field work.

Glotch organized an Apollo 11 50th Anniversary Event with the Montauk Observatory that was held in Southampton, NY on July 20. The event featured (1) a roundtable discussion between retired Grumman engineers who worked on the development of the LEM, (2) a presentation of official citations to the engineers by NY Assemblyman Fred Thiele “for their invaluable contributions to the space program,” (3) a lecture by Glotch on the Scientific Legacy of the Apollo Missions, (4) a screening of the Apollo 11 documentary, and (5) a post-screening Q&A with Ben Feist, who led the documentary team that restored 11,000 hours of mission control audio to bring the silent footage back to life.

3.3 Red Sox NASA STEM Day

On September 19, 2019, Glotch and RIS4E students and postdoctoral researchers from Stony Brook University, along with NASA scientists from around the country, shared highlights of NASA science and exploration activities with over 4,000 students and teachers from all over New England at Fenway Park. The RIS4E team supported the event by hosting a booth and talking with students and teachers. The event included demonstrations of impact processes (Figure 4.1), a group volcano-building activity, a demonstration of the differences between visible and infrared light, and a meteorite display. After the event, teachers were sent home with a packet of materials for their classrooms, in order to continue the science discussed at the stadium.

Figure 4.1. Stony Brook undergraduate student Alexander Kling demonstrates how meteor impacts can reveal buried rock layers at the surface in the crater ejecta.

4. Student/Early Career Participation

Undergraduate Students

1. Alexander Kling, Stony Brook University, Raman spectroscopy of impact shocked basalts
2. Grace Kim, Preparation of Bennu spectral analog mixtures
3. Melvin Li, Stony Brook University, Macrophage response to lunar soil simulants
4. Katie Luc, Stony Brook University, Assessment of genetic damage caused by lunar dust simulants
5. Rami Areikat, Stony Brook University, Assessment of genetic damage caused by lunar dust simulants
6. Oliver Lockwood, Stony Brook University, Mineral synthesis and characterization
7. Kristina Finnelli, Stony Brook University, Infrared spectroscopy of basalts from Hawaii and New Mexico
8. Lindsey Rollosson, Harvey Mudd College, Mineral sample preparation and characterization
9. Jane Watts, Harvey Mudd College, Mineral sample preparation and characterization
10. Danielle Michaud, Harvey Mudd College, Mineral sample preparation and characterization
11. Sydney Wallace, Harvey Mudd College, Machine learning applied to asteroid taxonomy
12. Miriam Eleazer, Mount Holyoke College, Spectroscopic data analysis
13. Adam Leschowicz, Purdue University, Spectroscopy environment chamber design/construction

Graduate Students

1. Laura Breitenfeld, simulated asteroid environment spectroscopy, multivariate modeling for spectral mixture analysis
2. Melissa Sims, Stony Brook University, Novel high pressure/temperature mineral physics experiments (now a postdoctoral researcher at Johns Hopkins University)
3. Melinda Rucks, Stony Brook University, Synthesis and characterization of tissintite (now a postdoctoral researcher at Princeton University)
4. Carey Legett IV, Stony Brook University, Light scattering models and space weathering experiments (now a postdoctoral researcher at Los Alamos National Laboratory)
5. Jordan Young, Stony Brook University, Raman spectroscopy of carbon in chondrite meteorites
6. Donald Hendrix, Stony Brook University, EPR and XPS spectroscopy of lunar analog dust
7. Tristan Catalano, Stony Brook University, Pigeonite synthesis and electron microprobe characterization
8. Douglas Schaub, Stony Brook University, Plagioclase synthesis and electron microprobe characterization
9. Kaitlyn Koenig Thompson, Stony Brook University, Lung inflammation processes
10. Nathan Smith, Northern Arizona University, Phobos thermal modeling
11. Marina Gemma, Columbia University, Simulated asteroid environment spectroscopy of ordinary chondrites

Postdoctoral Fellows

1. Rachel Caston, Stony Brook University, Assessment of genetic damage caused by lunar dust simulants (now a postdoctoral researcher at Indiana University)
2. Katherine Shirley, Stony Brook University, Thermal IR spectroscopy in a simulated lunar environment (now a postdoctoral researcher at University of Oxford, UK)

5. Mission Involvement

1. Lunar Reconnaissance Orbiter, Timothy Glotch, Diviner Lunar Radiometer Experiment, Co-I
2. Lunar Reconnaissance Orbiter, Neil Bowles, Diviner Lunar Radiometer Experiment, Co-I
3. Lunar Reconnaissance Orbiter, Noah Petro, Project Scientist
4. OSIRIS-REx, Timothy Glotch, OTES/OVIRS, Participating Scientist Co-I
5. OSIRIS-REx, Deanne Rogers, OTES/OVIRS, Participating Scientist Collaborator
6. ORISIS-REx, Christopher Edwards, OTES, Participating Scientist Collaborator
7. OSIRIS-REx, Neil Bowles, Co-I/Sample scientist—spectroscopy
8. OSIRIS-REx, Thomas Burbine, Collaborator/Asteroid scientist—spectroscopy
9. ORISIS-REx, Ed Cloutis, Co-I/Asteroid scientist—spectroscopy
10. Emirates Mars Mission, Christopher Edwards, EMIRS, Instrument Scientist
11. 2001 Mars Odyssey, Deanne Rogers, THEMIS, Co-I
12. 2001 Mars Odyssey, Christopher Edwards, THEMIS, Co-I
13. 2001 Mars Odyssey, Scott McLennan, GRS, Co-I
14. Mars Science Laboratory, Christopher Edwards, Participating Scientist
15. Mars Science Laboratory, Darby Dyar, ChemCam, Participating Scientist
16. Mars 2020, Joel Hurowitz, PIXL, Deputy PI

SSERVI Evolution and Environment of Exploration Destinations (SEEED)

Carlé Pieters
Brown University, Providence, RI

1. SEEED Team Report

The SEEED team has addressed detailed investigations of the chemical and thermal evolution of planetary bodies, the origin and evolution of volatiles, space weathering of regolith in different environments of long-term interest to NASA (the Moon and airless small bodies), and science and engineering synergism. During this last year of significantly limited SSERVI funds (no-cost extension), several SEEED themes and topics were nevertheless able to contribute to current and future lunar and asteroid science and exploration endeavors. Most have been leveraged though university and other supplemental R & A funding. Particular emphasis has been on training and mentoring the next generation of leaders for these important NASA endeavors.

1.1 Evaluating Cross-Cutting Roles of Ti (ilmenite) in Lunar Geochemistry

When lunar samples were first returned by Apollo 50 years ago, it was readily recognized that the lunar maria are volcanic in nature and basaltic in composition. However, compared to their terrestrial counterparts, lunar basalts are ancient (≥ 3 By), much lower in volatile components, and often significantly richer in Ti-bearing minerals. Lunar samples and a never-ending improvement of analytical approaches continue to illuminate our understanding of these Earth-Moon differences and their implications for planetary evolution and exploration.

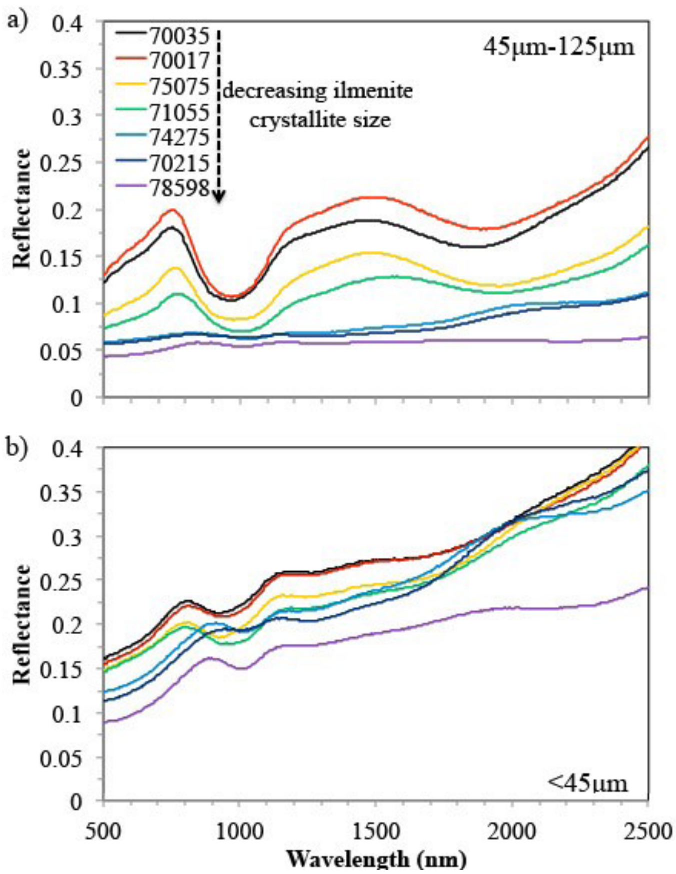
1.1.1 Constraints on the Character of the Source Region of Ti-rich Mare Basalts

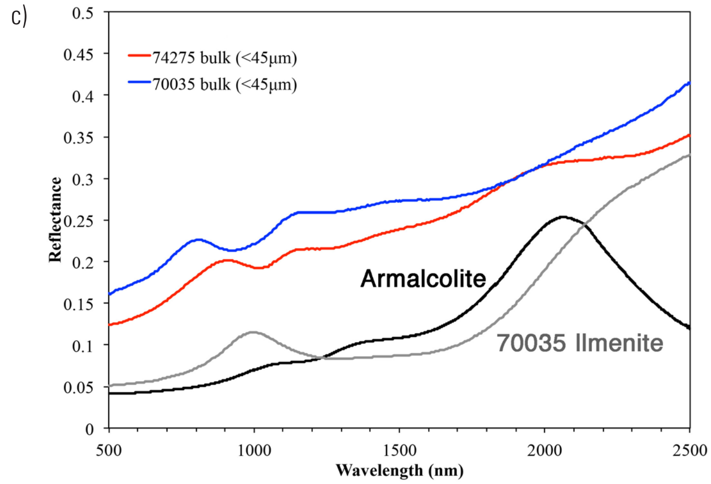
Although the lunar mantle cannot be sampled directly, mare basalts result from (re)melting of the mantle and are thus an indirect sample from the interior of the Moon. Ongoing experimental approaches with ultramafic glasses reported at LPSC 50 and 51 (Dygert et al, 2019; Brodsky et al., 2019; Guenther et al., 2019, 2020; Brown et al., 2020) constrain the depth of origin of the ilmenite bearing cumulate and may require mixing below the base of the primordial magma ocean. Results are shown to be sensitive to volatile content and f_{O2} of the evolving mantle.

1.1.2 Spectroscopic Properties of Lunar Opaques Improves Evaluation of Ti-rich Materials

Remote characterization of opaque-rich high-Ti basalts has been challenging for decades because opaques significantly mask diagnostic mafic mineral absorptions. Only recently has it been recognized that diverse lunar Ti-rich opaques also impart their own diagnostic spectral signatures that alter the shape of dominant pyroxene and olivine absorptions. In particular, the Mg content of ilmenite as well as the common presence of ferrous armalcolite are shown to imprint highly diagnostic spectral features in fine-grained Ti-rich lunar materials (Robertson et al. 2020). This discovery opens new approaches that can greatly improve assessment of unsampled lunar basalts and their soils using high quality near-infrared spectra.

(Robertson, K., R. Milliken, C.M. Pieters, L. Tokle, L. Cheek, and P. Isaacson (2020) Textural and Compositional Effects of Ilmenite on the Spectra of Hi-Titanium Lunar Basalts, Icarus in final review).





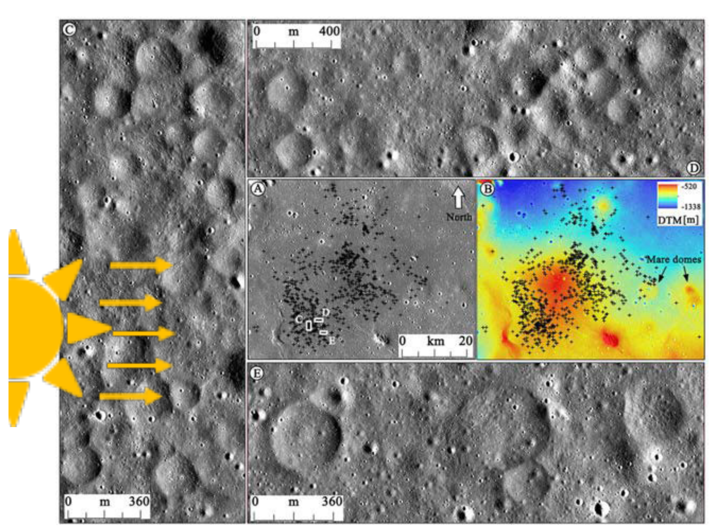
Reflectance spectra of Ti-rich Apollo 17 lunar basalts. a) Coarse particulate samples which exhibit different inherent textures are shown with decreasing crystal grain size. The samples with larger inherent grain sizes (red-green) exhibit characteristic absorptions diagnostic of Ca-rich pyroxenes. b) The same samples prepared as finer particle size samples. In this form, the presence of abundant opaques exhibits stronger influence on diagnostic absorptions as well as the continuum. c) Two representative basalt spectra from (b) along with fine particulates of Mg-bearing 70035 ilmenite and synthetic armalcolite. The diagnostic spectral features of these fine grained opaques strongly influence absorptions present in lunar Ti-rich basalts and their soils

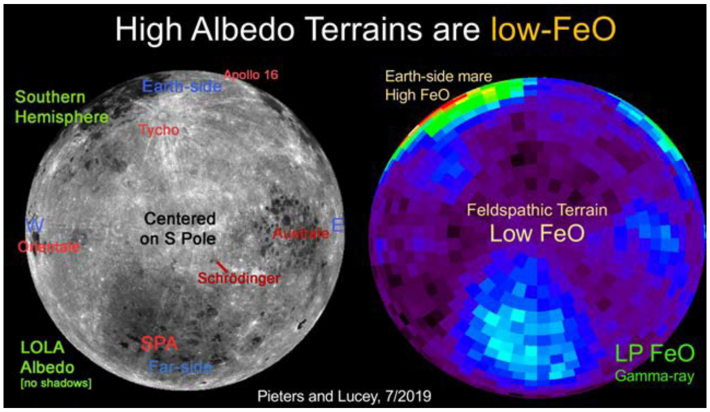
1.2 Modeling Unusual Clustered Lunar Circular Features to Constrain their Volcanic Origin

Look again!! These are not all lunar craters. As described by *Wilson et al. (2019)*, this concentration of small low mounds occurs in the lunar maria and appears to form synchronously with the surrounding mare basalt deposits. They are described analytically and interpreted to be due to inflation of the molten cores of cooling flows during the late stages of eruptions by injection of additional hot lava containing dissolved volatiles. This model makes predictions that can be tested by further observations of the morphology, morphometry, and distribution of RMDSs and the regolith developed upon them (Wilson, L., J. W. Head III, and F. Zhang (2019), A theoretical model for the formation of Ring Moat Dome Structures: Products of second boiling in lunar basaltic lava flows, J Volcanol Geoth Res, 374, 160-180. doi: 10.1016/j.jvolgeores.2019.02.018).

1.3 Integrated Remote Sensing Data of Lunar Poles Indicate Feldspathic Bulk Composition

The character of the lunar poles and their potential resources (volatiles) are of great interest to NASA andother space-faring entities as plans are made for future exploration of these enigmatic regions. Because solar radiation is minimal and some polar areas are in permanent shadow, useful compositional data from remote sensing techniques that rely on solar illumination is sparse. Nevertheless, two independent data sources [LOLA laser 1 μm albedo with zero shadows and LP gamma ray data] provide the same result: the lunar





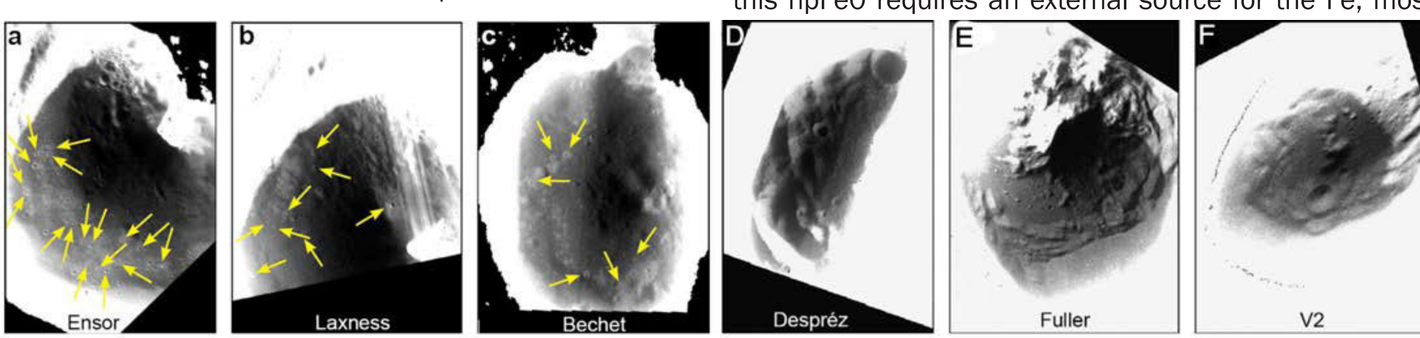
poles are comprised of feldspathic highland breccias similar to that sampled at Apollo 16 and Luna 20. Areas containing more mafic-rich materials are 100s of km away (Information package prepared for HEOMD/AES by C.M. Pieters and P.G. Lucey (July, 2019)).

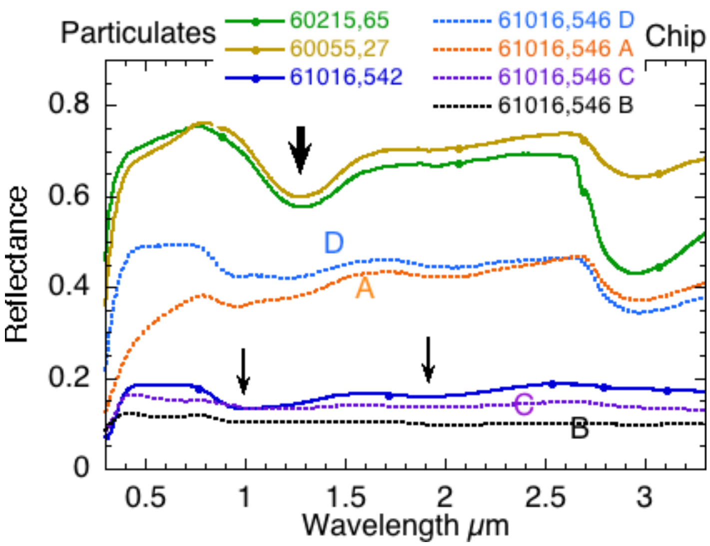
1.4 Age of Mercury's Polar Ice Constrained to be Recent from Crater Statistics

The low altitude imaging of Mercury polar regions by MESSENGER enabled Deutsch et al. (2019) to identify and evaluate the record of small craters using scattered light within the permanently shadowed regions (PSR) of large craters hosting water-ice deposits. Each of the analyzed large craters is located below ~86°N and has a low-reflectance layer of materials within its PSR. Some host craters (a, b, c) contain small craters that exhibit surrounding brightness variations suggesting that these small craters superpose the ice deposits, whereas other host craters (D, E, F) lack craters with such brightness rings and suggest no craters superimpose the deposits. A combined analyses of Poisson statistics and the direct observations of small crater statistics provide conservative age estimates that the ice was delivered to Mercury within the last ~330 Myr or younger. This young age of Mercury ice is consistent with previous independent analyses of the ice purity and regolith gardening and is in marked contrast to the diffuse inferred deposits on the Moon. Deutsch, A. N., J. W. Head III, and G. A. Neumann (2019), Age constraints of Mercury's polar deposits suggest recent delivery of ice, Earth and Planetary Science Letters, 520, 26-33, 10.1016/j.epsl.2019.05.027.

1.5 Returned Sample Shows Key Lunar Space Weathering Products Occur Rapidly (<2 Ma)

Most information about lunar space weathering comes from studying the complex properties of lunar soils and weathering products that gradually accumulate on and in soil grains during regolith evolution. Compared to unweathered rocks, well-developed soils typically exhibit weaker mineral absorption bands, a continuum sloped toward longer wavelengths, and a lower albedo at visible wavelengths. Because space weathering consists of stochastic processes at multiple scales involving repeated cycles of shock, brecciation, melting, vaporization, irradiation, mixing, etc., it has not been possible to define a time scale for space weathering of lunar soils. As part of an investigation into shock effects on lunar plagioclase optical properties Pieters et al. (2020) requested a chip of a heavily shocked plagioclase sample from 'Big Muley' 61016. This large rock was shocked and excavated by South Ray Crater 2 Ma ago and remained undisturbed until documented and collected by Apollo 16 astronauts. The highly shocked anorthosite 'cap' [chip area D] contains no mafic minerals, but consists of a combination of crystalline plagioclase and the shocked equivalent maskelynite (glass). This mineral combination is seen both petrographically as well as in the spectra. A vitreous coarse grained sample below the cap [61016,542] is almost entirely maskelynite (glass). The surface of the plagioclase 'cap' exposed to the lunar environment for 2 Ma, however, developed a pervasive patina and exhibits [chip area A] the classic signature of nano-phase Fe0, a principal marker of lunar space weathering. The origin of this npFe0 requires an external source for the Fe, most



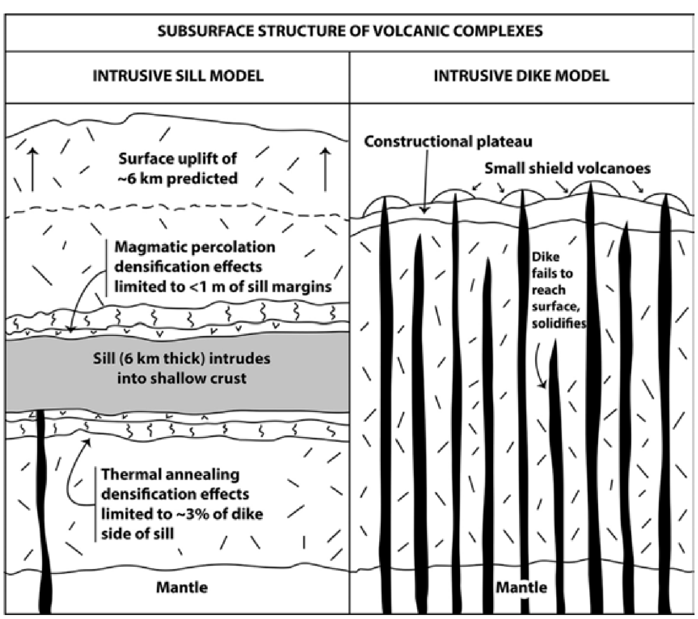


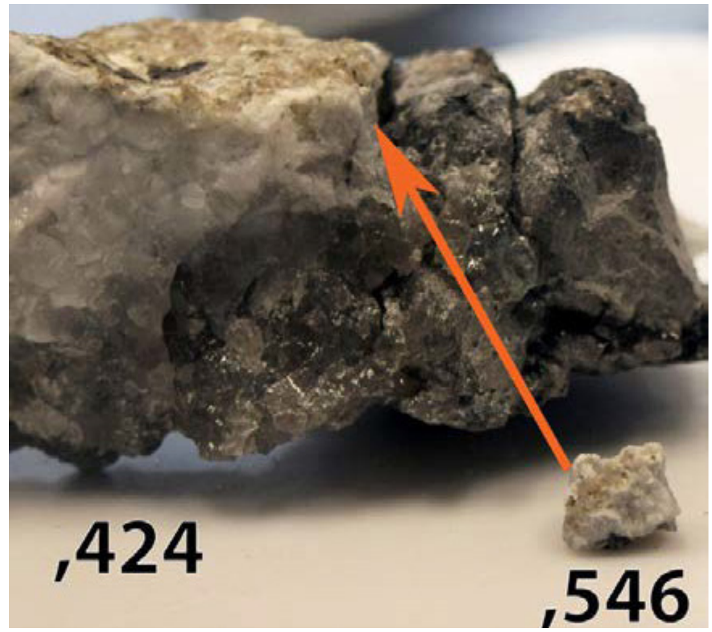
Reflectance spectra of 2 particulate anorthosite samples and four areas on the small chip of 61016,546. **Thick black arrow** indicates an absorption diagnostic of crystalline plagioclase; **small arrows** indicate two absorption bands diagnostic of maskelynite (shocked plagioclase diaplectic glass).

likely derived from micrometeorites over 2 Ma. (C.M. Pieters, G. R. Osinski, T. Hiroi (2020) Rapid (<2Ma) Lunar Space Weathering Products Indicated by Apollo 16 'Big Muley' Sample 61016, LPSC51 #1618).

1.6 The Geology and Structure of the Lunar Marius Hills Volcanic Complex

Marius Hills is a volcanic complex region that exhibits a significant gravity anomaly in Oceanus Procellarum (Deutsch et al., 2019). While shallow crustal country rock on the Moon is highly fractured, GRAIL gravity data has shown deeper crustal material is also more porous than





Portion of the shocked anorthositic cap of 'Big Muley' 61016. The location of the ~6 mm 61016,546 chip from the anorthosite cap is indicated. Area A contains the exterior patina, and D is shocked plagioclase directly below.

'Big Muley' 61016 in the field at Apollo 16.

previously thought. Focusing on the Marius Hills region in this context Head and Wilson (2020) quantitatively analyze emplacement of deep basaltic dikes and sills on the Moon that could account for the gravity anomaly.

They assess the consequences of cooling and heat loss and conclude that solidified dikes in the Marius Hills region can constitute 30–50% of the crust, creating a substantial Bouguer gravity anomaly as observed. The dike model is preferred over an intrusive sill model largely because the latter predicts uplift complications that are not observed (Deutsch, A. N, G. A. Neumann, J. W. Head III, and L. Wilson (2019), GRAIL-identified gravity anomalies in Oceanus Procellarum: Insight into subsurface impact and magmatic structures on the Moon, Icarus, 331, 192-208, doi: 10.1016/j.icarus.2019.05.027. Head III, J. W., and L. Wilson (2020), Magmatic intrusion-related processes in the upper lunar crust...., Planetary and Space Science 180, doi.org/10.1016/j.pss.2019.104765.

1.7 Geologic Constraints of the South Pole High Illumination Site: Mons Malapert

2. Inter-team/International Collaborations

The majority of SEEED peer-reviewed publications in 2019/2020 were undertaken with international collaborators or members from other SSERVI teams. [See details found on our website: http://www.planetary.brown.edu/html_pages/brown-mit_sservi_pubs.htm]

2.1 International Collaborations and Participation

Specific products for 2019/2020 resulting from interactions with SEEED international partners include:

Russia: we have maintained long-term productive collaborations with Russian planetary science colleagues [see above section 1.7 discussing Mons Malapert by SEEED collaborator *Basilevsky et al. (2019)*]. Person-to-person science interactions have been able to continue on a regular basis at meetings such as the annual Moscow International Solar System Symposium.

Ukraine: although regular interactions are more difficult to arrange with SEEED colleagues from the Ukraine, they always result in innovative and insightful joint activities [see *Shkuratov et al. (2019)*].

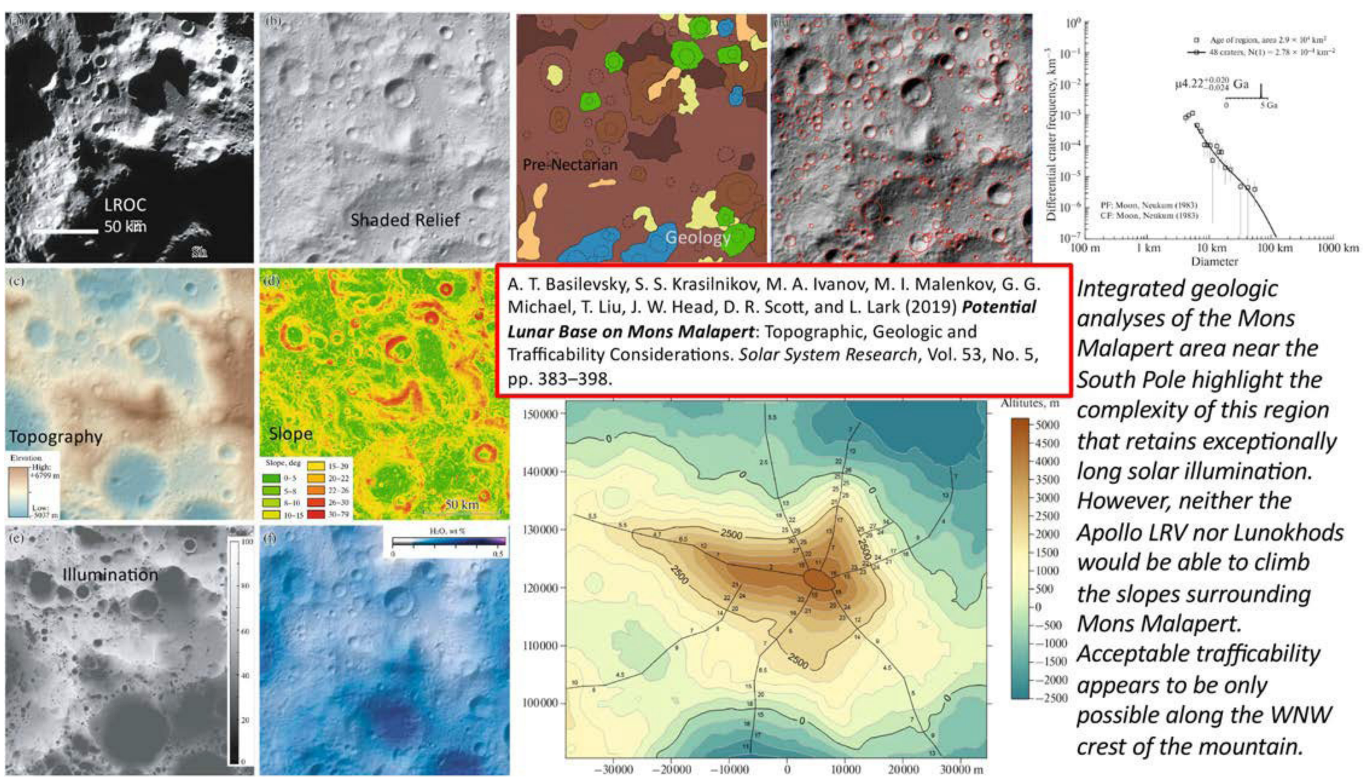
Canada: our collaboration with Dr. Gordon (Oz) Osinski (SSERVI International PI in Canada) focuses on integrated analyses to understand the physical effects and optical signature of shock on lunar materials.

Coordinated analyses benefit greatly from the detailed experience of both teams, often in unpredictable ways [see section 1.1.2 (Pieters et al., 2020 LPSC51)].

Japan: based on their extensive work with primitive meteorites and spectroscopy, Co-Is Hiroi and Milliken were invited to participant in some of the Hayabusa II Ryugu encounter analyses, a highly productive and insightful activity. [see *Barucci et al., (2019); Sugita et al., (2019)*].

England: the ongoing partnership between L. Wilson and J. W. Head interweaving physical and geological understanding of planetary volcanism has continued to produce keen insight into the diverse manifestations of these fundamental processes. Examples include sections 1.2 and 1.6 above [see *Head and Wilson, 2020; Qiao et al., 2019; Wilson et al., 2019*].

In addition, SEEED scientists renewed friendships and



Integrated geologic analyses of the Mons Malapert area near the South Pole highlight the complexity of this region that retains exceptionally long solar illumination. However, neither the Apollo LRV nor Lunokhods would be able to climb the slopes surrounding Mons Malapert. Acceptable trafficability appears to be only possible along the WNW crest of the mountain.

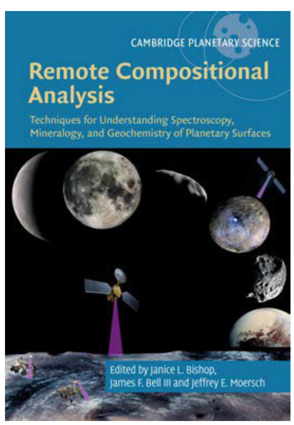
mutual science interests with diverse international colleagues by actively participating in several international planetary science gatherings held in Europe, Japan, and Russia. These included: European Lunar Symposium [Manchester, England May 21-23], METSOC [Sapporo, Japan July 7-12], DPS/EPSC [Geneva, Sept. 15-21], and the 10th Moscow International Solar SystemSymposium (10M-S3) [Moscow Oct. 7-11].

2.2 Example Inter-Team Interactions (SEEED-RIS^{4}E-VORTICES)

The culmination of several years' efforts produced an important and much-needed textbook, *Remote Compositional Analysis*. SEEED scientists led two key chapters working with members of two other SSERVI teams as co-authors:

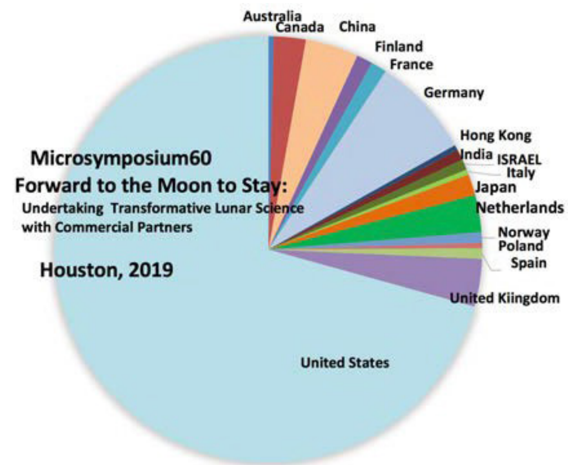
Mustard, J. F., and T. D. Glotch (2019), Theory of Reflectance and Emittance Spectroscopy of Geologic Materials in the Visible and Infrared Regions, *Chapter 2* in *Remote Compositional Analysis: Techniques for Understanding Spectroscopy, Mineralogy, and Geochemistry of Planetary Surfaces*, edited by J. L. Bishop, J. E. Moersch and J. F. Bell III, pp 21-41. Cambridge University Press, Cambridge, UK.

Pieters, C. M., R. L. Klima, and R. O. Green (2019), Compositional Analysis of the Moon from the Visible and Near-infrared, *Chapter 18* in *Remote Compositional Analysis: Techniques for Understanding Spectroscopy, Mineralogy, and Geochemistry of Planetary Surfaces*, edited by J. L. Bishop, J. E. Moersch and J. F. Bell III, pp 368-392. Cambridge University Press, Cambridge, UK.



3. Public Engagement Activities

All SEEED activities are naturally interwoven with Public Engagement interactions and communication. A few examples are highlighted here:



3.1 Microsymposium 60: Forward to the Moon to Stay: Undertaking Transformative Lunar Science with Commercial Partners: March 16-17

Invigorating discussions and interactions! Final statistics: 255 participants from 17 countries.

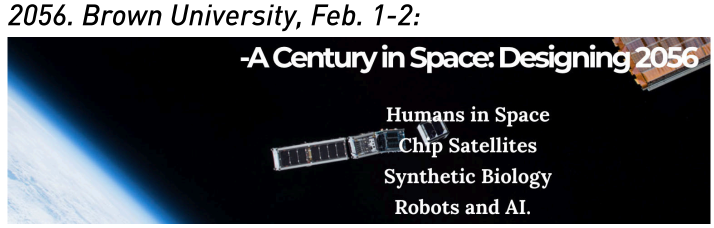
3.2 RI Robotic Block Party, April 19

Open (free) science and robotic discussions and demonstrations for all ages. Everyone loved the 3-D printed planetary topography and lander models. SEEED students were enthusiastic and knowledgeable hosts.

3.3 Apollo 50th Celebration in Providence, July

SEEED activities were co-sponsored with RI Space Grant and included a three week "Museum of the Moon" available free to the public along with multiple science-for-the- public lectures. Events culminated on July 20th with a special lunar themed Waterfire which also included our booth for the SEEED-SSERVI 'Touch the Moon' interactive display* (and a long line.....) [*our unweathered lunar feldspathic breccia meteorite certified to be an actual piece of the Moon]

3.4 Space Horizons 2019, A Century in Space: Designing 2056. Brown University, Feb. 1-2:



Co-sponsored with Engineering and led by students. Discussion on the themes: Humans in Space, Chip Satellites, Synthetic Biology, Robots and Artificial Intelligence. Activities and meeting with students included

During LPSC (March 18-22) a joyful young undergradvolcanologist [Molly Brown from Frisco, TX] sent us this photo after finding her poster was next to ‘the work of two epic researchers!

interactive workshop with two NASA astronauts [James Newman and Jeff Hoffman] and NASA Ames SSERVI collaborator Lynn Rothschild, focusing on envisioning the future. [https://www.spacehorizonsatbrown.org/]

4. SEEED Student/Early Career Participation and Co-I Transitions 2019/2020:

SEEED undergraduate students, graduate students, and postdoctoral fellows are active in lunar and small bodies exploration and research. They participate in professional science meetings (largely LPSC, NESF, AGU and focused workshops) for discussion with colleagues and presentations of their research. Several are also committed to ongoing outreach activities.

Undergraduate Students

1. Megan Guenther, MIT; experimental petrology with lunar compositions
2. Finnian Lowden, Brown University; Mercury/Moon unit age dating and volatile production
3. Dylan Villeneuve, Brown University; Mercury/Moon unit age dating and volatile production

Graduate Students

1. Brendan A. Anzures, Brown University; meteorite geochemistry
2. Benjamin Boatwright, Brown University; Modeling diffusive landscape degradation processes; Public Engagement at Ladd Observatory
3. Michael Bramble, Brown University; Asteroid and lunar environment [ALEC] spectroscopy
4. Ariel Deutsch, Brown University; Polar and circumpolar ice deposits, Moon and Mercury; Public Engagement education activities
5. Elizabeth Fisher, Brown University; Vesta mineralogy, lunar OH/H2O experiments
6. Christopher Kremer, Brown University; Developing spectroscopy tools for 3 – 8 μm spectra; Public Engagement at RI Robot Block party and Lunar 50th celebrations
7. Clara Maural, MIT; meteorite paleomagnetic analyses
8. Saied Mighani, MIT; evolution of lunar magnetism [now at Stanford]
9. Cody Schultz; Brown University; (1st year) learning ALEC applications
10. Jesse Tarnas, Brown University; Hyperspectral imaging applications
11. Leif Tokle, Brown University; chemistry and spectroscopy of opaque minerals

Postdoctoral Fellows

1. Charles-Edouard Boukaré, Brown University (now in France), Modelling of lunar magma oceans and aftermath.
2. Stephanie M. Brown, MIT; Experimental petrology, lunar utramafic compositions
3. Kevin Robertson, Brown University, Laboratory studies of lunar and asteroidal materialsElizabeth Sklute, Mount Holyoke College, Spectroscopy of mineral mixtures

Co-I/Faculty Transitions

1. Brandon Johnson, Assistant Prof., Brown University; Now at Purdue University

5. Mission Involvement

Below is a list of some of the mission activities for which SEEED PI/Co-Is are or have been involved. [Planned or upcoming missions are incomplete.]

Mission	SEEED Investigator	Instrument/Experiment	Role
Chandrayaan-1	Pieters, Carle	Moon Mineralogy Mapper	Instrument PI
Chandrayaan-1	Head, Jim	Moon Mineralogy Mapper	Co-I
Chandrayaan-1	Mustard, Jack	Moon Mineralogy Mapper	Co-I
Chandrayaan-1	Runyon, Cass	Moon Mineralogy Mapper	EPO-Co-I
Dawn	Pieters, Carle	Science Team	Co-I
Dawn	Zuber, Maria	Science Team	Co-I
Mars Ex (Phobos)	Head, Jim	HRSC	Co-I
LCROSS	Schultz, Peter	Science Team	Co-I
LRO	Zuber, Maria	LOLA	Instrument PI
LRO	Head, Jim	LOLA	Co-I
MESSENGER	Head, Jim	Science Team	Co-I
GRAIL	Zuber, Maria	Discovery Mission	Mission PI
GRAIL	Head, Jim	Science Team	Participating Scientist
GRAIL	Evans, Alex	Science Team	Affiliate
OSIRIS REx	Binzel, Rick	Science Team	Co-I
Hayabusa 2	Hiroi, Takahiro	NIRS3 [JAXA invited]	Affiliate
Hayabusa 2	Milliken, Ralph	NIRS3 [JAXA invited]	Affiliate
Psyche	Elkins-Taunton, Lindy	Discovery Mission	Mission PI
Psyche	Weiss, Ben	Magnetometer	Instrument PI
Psyche	Zuber, Maria	Radio Science	Instrument PI
Psyche	Binzel, Rick	Asteroid Composition	Co-I
SpaceIL	Head, Jim	New Lunar Mission	Science Team
SpaceIL	Weiss, Ben	New Lunar Mission	Science Team
Lunar Trailblazer	Pieters, Carle	SIMPLEX	Co-I
UCIS-Moon	Pieters, Carle	DALI	Collaborator
MoonDiver	Head, Jim	Discovery Concept	Co-I
MoonDiver	Pieters, Carle	Discovery Concept	Co-I
LVO	Pieters, Carle	Discovery Concept	Co-I
NanoSWARM	Pieters, Carle	Discovery Concept	Co-I

6. SEEED Awards

Maria Zuber (SEEED Co-I) received the prestigious DPS Gerard P. Kuiper Prize:

The Division for Planetary Science (DPS) of the American Astronomical Society awarded the 2019 Gerard P. Kuiper Prize for outstanding contributions to the field of planetary science to Maria Zuber (MIT) for her contributions to advancements in geophysics, planetary gravity mapping, and laser altimetry. One example of her seminal contributions includes her paper in *Science* in 2000 combining Mars Global Surveyor laser altimetry data and gravity data to determine the crustal and upper mantle structure of Mars.

Another example is her leadership as principal investigator of the GRAIL mission to construct a model of the Moon's gravitational field to spherical harmonic degree 1,800, which exceeds the baseline requirement of the mission by an order of magnitude. Dr. Zuber has turned her attention to many different solid bodies in the Solar System including Mercury, Venus, Eros, Vesta, and Ceres. Over the years she has advised a number of students and postdocs, and one reports that she strikes the perfect balance of being demanding, supportive, encouraging, and open minded.

James W. Head (SEEED Deputy-PI) received the Geological Society of Washington's Great Dane Award for best informal communication to the society of timely or newsworthy events (discussions of current lunar exploration).

LPSC50 Special Session Invited Presentations, *50 Years of Lunar Science: The Legacy of "One Small Step:"*

SEEED Collaborator **Harry Hiesinger** The Lunar Apollo Missions: Enabling Dating of Planetary Surfaces Throughout the Solar System

SEEED Co-I **Maria Zuber** Geophysics and Shallow Internal Structure of the Moon

SEEED PI **Carle Pieters** Global Composition of the Moon (As We're Learning to Know It)

SEEED Students received Dwornik 2019 Awards for presentations at LPSC50:

- Best Graduate Oral: **Clara Maurel**, MIT, *"Partial Differentiation and Magnetic History of the IIE Iron Meteorite Parent Body."*
- Honorable Mention Undergraduate Oral: **Christopher Yen**, Brown University

Ariel Deutsch (SEEED Senior Graduate student):

- Awarded a LPI Career Development Award for LPSC 50
- Served on the SSERVI Apollo 50th Anniversary Panel on the USS Hornet [with Harrison H. "Jack" Schmitt, David Kring, and Jen Heldmann, moderated by Jake Bleacher] (July 24, 2019)
- Received a Larry Taylor travel award to participate in the Fall LEAG meeting in WDC (Oct. 26-28, 2019)
- Was selected for Brown's Dissertation Writing Retreat (Jan 13-17 2020), sponsored by the Graduate School, Sheridan Center, and Writing Center at Brown

Volatiles Regolith & Thermal Investigations Consortium for Exploration and Science (VORTICES)

Andy Rivkin

Johns Hopkins University/ Applied Physics Lab, Laurel, MD

1. VORTICES Team Report

The Volatiles, Regolith and Thermal Investigations Consortium for Exploration and Science (VORTICES) team has been carrying out research since 2014 on four broad themes: “Volatiles: Sources, Processes, Sinks;” “Regolith Origin and Evolution;” “Resource Identification;” and “Strategic Knowledge Gap Analysis.” In the intervening time, significant cross-theme and interdisciplinary work has occurred. Therefore, the sections below are aligned with current research avenues.

1.1 Lunar and Asteroidal Volatiles

The formation, transport, and destruction or sequestering of lunar volatiles has been a major research interest of VORTICES Co-Is since before the team’s beginning: VORTICES evolved from an NLSI team focused on lunar volatiles. The final years of VORTICES are bringing some of the major questions in lunar volatile studies to closure, as geochemical and geophysical pathways are being studied in tandem with reconsideration of remote sensing data. In addition, VORTICES-sponsored work on the distribution of asteroidal volatiles has implications for ISRU/asteroid mining and for lunar science.

1.1.1 Lunar Volatile Distribution and Transport

1.1.1.1 Anatomy of the Water Vapor Exosphere of the Moon

Hurley et al. simulated the distribution of water in the Moon’s exosphere for a variety of release mechanisms and surface interactions in order to determine if exospheric measurements could be used to decipher which processes are involved in the ongoing lunar water cycle. They found that measuring the local time distribution of exospheric water is diagnostic of the source of water—either meteoroid impacts or solar wind in the case when water does not migrate on more than one hop after its initial release, as shown in the top panel of Figure 1. In the case when water does migrate on more than one hop after the subsequent release, the local time distribution of exospheric water can be used to extract information about the surface interaction. As shown in the bottom panel of Figure 1, the location of the peak density is related to the temperature at which the residence time

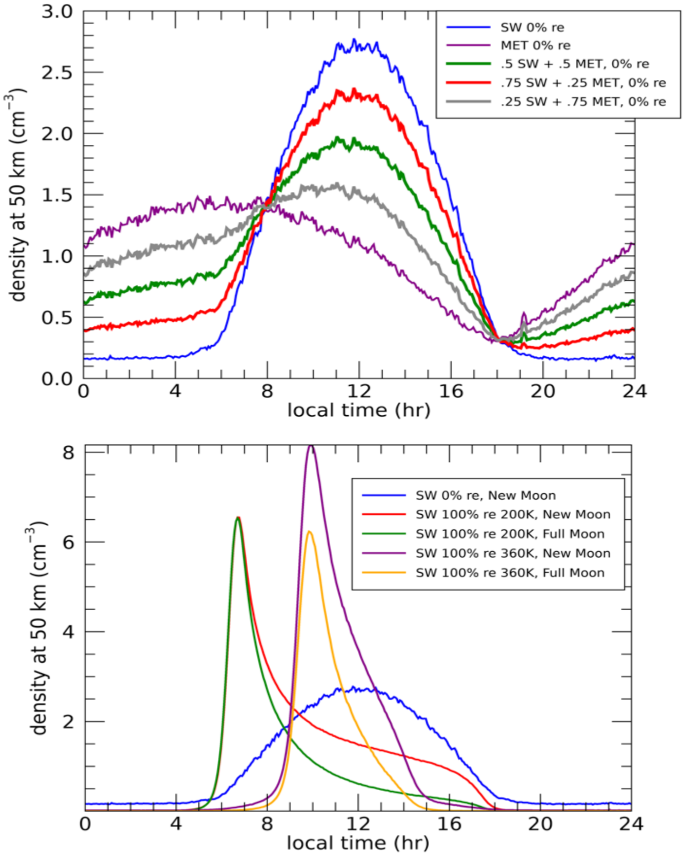


Figure 1:Work by the VORTICES team shows the time distribution of lunar exospheric water can be used to determine either the source of the water (top panel) or its interaction with the surface (bottom panel).

for water on the surface is short. In this case, changes in the exospheric water density during passages through the Earth's magnetotail can be used to differentiate a solar wind source from a meteoroid source.

1.1.1.2 Simulations of Transport of CO_2 Ice on the Moon

Hurley et al. simulated the delivery efficiency of CO_2 through the Moon's exosphere to relate the amount of CO_2 that would need to be delivered to the Moon to result in the deposition of a given amount of CO_2 ice in the lunar cold traps. This work was motivated by observations of an albedo change at very low temperatures on the Moon consistent with the presence of CO_2 ice or another volatile in cold traps. They found that the amount of CO_2 needed to be released somewhere on the Moon to deliver a 1 mm thick layer in the area with maximum temperature < 55 K is equivalent to the amount of CO_2 expected in a 500 m comet.

1.1.1.3 Hydration in Meteorite and Mineral Samples

VORTICES funding has helped support detailed analysis of the spectral nature of 20 carbonaceous chondrite meteorite samples. The work, conducted in LabSPEC, by Hibbitts and Stockstill-Cahill characterized the spectral nature of water in the 3 and 6-μm region. The spectra were collected in collaboration with Driss Takir, under ambient conditions, under vacuum at room temperature, and again at room temperature after having cooled from being exposed for 12 hours to 80 °C while under vacuum. As an example, reflectance spectra of the CM2 Crescent meteorite exhibit water-related 3 and 6-μm features, which are relatively stronger (meaning more water) for the spectra of the meteorite under ambient conditions. Unexpectedly, not only does the depth of the 6-μm feature decrease after heating the sample under vacuum, the position of the 6-μm feature shifts with water abundance as well. This effect has been observed for several of the other meteorite samples. VORTICES funding helped support the analysis of the 6 μm region of this dataset, which will be presented at LPSC in 2020, and supported Stockstill-Cahill and Hibbitts presenting their work at the REVEALS SSERVI all-hands meeting in Nov. 2019.

Klima has continued work investigating water in nominally anhydrous minerals, focusing both on remote sensing studies of the Moon as well as laboratory studies of terrestrial analogs and meteorites. On the remote sensing side, Klima is examining both the distribution of water/OH on the lunar surface and its association with olivine and low Ca pyroxene-bearing intrusive igneous lithologies. This work builds on the mapping work of former intern Jordan Bretzfelder (now a UCLA grad student), who identified several likely ultramafic (pyroxenite) massifs around the Imbrium basin. Klima is comparing the relative OH absorption bands observed at key massifs mapped in Bretzfelder's project. In the laboratory, Klima has recently received an Early Career Fellowship step two proposal, with which she will purchase an upgraded spectrometer to conduct improved microspectroscopic measurements of OH in terrestrial minerals and ordinary chondrites. In brief, these minerals are being measured in the UV-SWIR (~0.2-8 microns) by TREX Co-I Stockstill-Cahill (in an ongoing collaboration between VORTICES and TREX) under ultra-high vacuum (UHV) conditions and increasingly higher temperatures to characterize the shape and strength of the OH/water absorption band. These minerals will then be measured again in the microspectrometer to quantify the amount of OH in the mineral structure as well as the shape and position of the absorption bands in transmission. Together, these measurements will be fed into spectral models to assess the shape, position, and strength of adsorbed and internal water in key extraterrestrial minerals. These results were presented at the Meteoritical Society annual meeting as well as the European Planetary Science Congress.

1.1.1.4 Water Formation, Adsorption, and Evolution on Airless Surfaces

VORTICES funding has been used to support laboratory work at Georgia Tech (GIT), scientific presentations at two international conferences, and the submission of a peer-reviewed journal article (Jones et al.) that is now under second revision (available at https://smartech.gatech.edu/handle/1853/62011). Research related to water on the surface of the Moon focused on: 1. the formation of molecular water through non-equilibrium chemistry in the plumes created by micrometeoroid impact into solar wind saturated lunar grains, and 2. the adsorption of

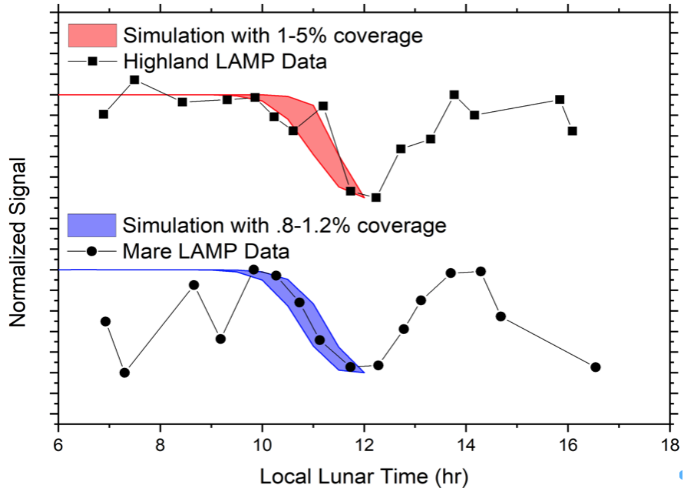


Figure 2: Using thermal activation energies derived in Jones et al. (in revision), the stability of adsorbed molecular water over a lunar day trends similarly to the observed diurnal UV signature of water.

molecular and dissociated water onto lunar soil grains and the water's subsequent evolution over multiple lunar days from a global perspective, including investigating a possible mechanism to explain the diurnal cycling of surficial water as observed in the UV (Fig. 2). Cahill and Greenhagen, in collaboration with Hendrix of TREX, are working to improve our understanding of LAMP far-UV measures of H_2O/OH as observed by LRO LAMP. Greenhagen and Cahill are providing Diviner temperature data and analysis support for a study led by Hendrix to examine hydration changes with latitude.

1.2 Remote Sensing Across Many Wavelengths

1.2.1 Space Weathering in the UV-NIR

Cahill, Stockstill-Cahill and Hibbitts performed UV spectral measurements of planetary analogs to investigate maturity effects. As in the NIR, spectral changes in the UV were shown to be indicative of the abundance of and size of nanometer- to micrometer-sized native iron disseminated in a silicate matrix, an analog for space weathering and associated maturity effects. Cahill and Blewett collaborated in a study to measure the optical constants of unoxidized vs. oxidized Fe and Ni optical constants from the FUV (160 nm) to the NIR (4100 nm) at higher spectral sampling. This was supplemented with modeling and analysis of mineral assemblages with a variety of submicroscopic Fe and Ni abundances at varying particle sizes. This should enable a more robust look at how weathering might affect analysis of the 3 um hydration feature on the Moon, as well as analysis of M-Type asteroids like Psyche.

1.2.2 Remote Sensing of Lunar Impact Flashes

During 2019, VORTICES supported analysis by Goldberg of visible and infrared (IR) image data taken during the total lunar eclipse which occurred on January 29, 2019. At the beginning of totality, there was flash associated with an impact event recorded by many observers. Goldberg observed the Moon during the eclipse with a suite of sensors, including visible (0.4 – 0.7 μm), short wavelength IR (SWIR 0.9 – 1.7 μm), medium wavelength IR (MWIR 3-5 μm), and long wavelength IR (LWIR 8-10 μm), to observe the changes in thermal signature of different regions of the lunar surface. The impact flash was recorded on a single frame by the visible camera and on 7 consecutive frames on the SWIR camera. Visible and SWIR Images of the flash are shown in Figure 3.

Analysis of the SWIR imagery showed that the peak intensity of the flash was approximately 500 MW/sr and that the total optical energy released in the event in the 0.9 – 1.7 μm band was approximately 127 MJ. The initial SWIR frame of the impact showed a pronounced asymmetry that implied that the impacting object hit the lunar surface at an angle of 45° or shallower and that it came from the direction of the lunar north.

With VORTICES support, Stickle used CTH to simulate impacts into the lunar surface, and modeled debris size and temperature/density fields near the surface following

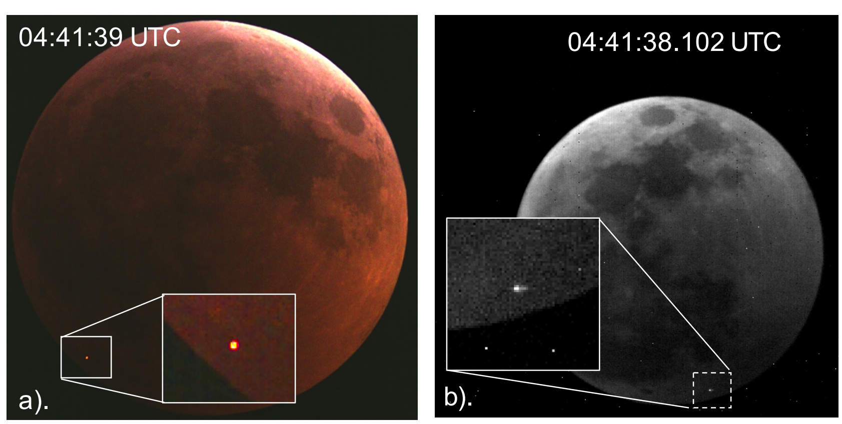


Figure 3: Visible (a) and SWIR (b) IR images of the impact event.

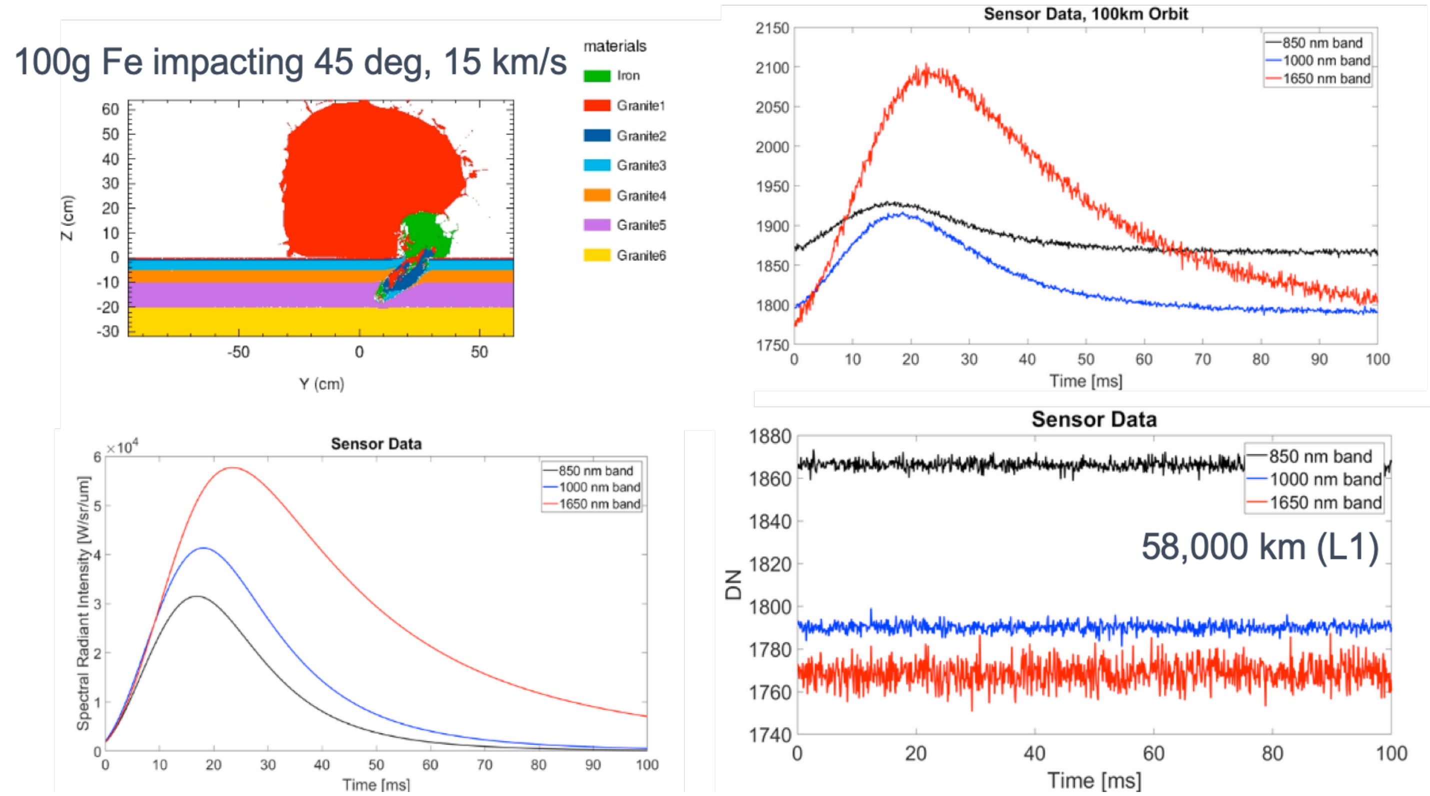


Figure 4: Example of a CTH simulation of a 100g Fe asteroid impacting the Moon at 15 km/s, showing the expansion of a vapor plume above the surface (upper left). The predicted impact flash signature in three wave-bands is shown (bottom left), as well as the potential signature that would be observed from two potential orbit locations: 100 km (upper right), and L1 (bottom right).

the impact, as illustrated in Fig. 4. These were done for two purposes: 1) to identify how many volatiles may be released after an impact, and 2) to use as a source term to model impact flashes (for instance, as observed during the eclipse). The temperature and density fields will feed into models for Hurley to investigate volatile density above the surface that could be observed using remote sensing techniques. The debris size and temperature fields are post-processed using an APL in-house code to determine the expansion of the plume and the magnitude of the light in the impact flash, and how that signature could be monitored using orbital or Earth-based sensors for potential future exploration opportunities.

Using these methods, Stickle modeled the Jan. 2019 lunar impact for comparison with the Goldberg observations. Initial results, presented at AGU, reproduced the observed flash well. Stickle compared simulated impact flashes for high- and low-density projectiles, various impact velocities, and impact angles. By comparing simulated light curves to those observed, they were able to constrain impactor geometry and composition. A more extensive analysis will be presented at LPSC and submitted to Icarus.

1.2.3 Neutron Studies of the Lunar Paleopole

Wilson, Lawrence, and others have been reconstructing Lunar Prospector (LP) epithermal neutron data to distinguish between different paleopole ice deposition hypotheses. The distribution of hydrogen observed in the Lunar Prospector neutron data at both poles does not match expectations based on present lunar temperatures. Additionally, the centroids of the hydrogen distribution are offset from the poles and antipodal to one another. These observations have been taken as evidence that the Moon's spin axis has shifted since the hydrogen was deposited (Siegler et al. 2016). This 'paleopole,' where the hydrogen was deposited, is taken to be coincident with the hydrogen distribution maxima.

As the neutron spectrometers on LP are omnidirectional, their footprint is proportional to the spacecraft's altitude. The low-altitude data have a 45 km FWHM footprint so are unable to resolve variation across features tens of km in size, such as polar craters and their surroundings.

Image reconstruction or modelling is required to learn about smaller-scale hydrogen variation. This involves choosing ‘decoupled regions’ which have a hydrogen content independent of the background. In the past the PSRs have been chosen as the decoupled regions. However, this choice implicitly assumes that only present-day stability is important to the current distribution of hydrogen. If the hydrogen exists not only in the PSRs (as ice), but as dispersed hydrated minerals, then the surface distribution may be better described with alternative decoupled regions.

We reconstructed a set of hydrogen distributions based on various combinations of present and paleopole-era thermal stabilities. These correspond to scenarios including those where all of the hydrogen-bearing material was deposited when the Moon had its present spin pole or paleopole; the hydrogen-bearing material was laid down at the paleopole and is able to persist because it is in the form of a hydrated mineral rather than ice; or hydrogen is present in the form of near-surface water ice that was deposited during the paleo-pole era and persists only in regions where water ice was stable both then and now.

Examination of the residuals imply that decoupling is required as the residuals from the coupled reconstruction show a systematic positive bias within the potential decoupled regions. At the north pole any of the decoupling schemes are sufficient to achieve a good fit. At the south pole the simple paleopole decoupling is ruled out but all other cases are allowed. Initial results were presented at LPSC in 2019, and a paper to JGR-Planets is in preparation.

1.2.4 Thermal Modeling and Asteroid Hydration

A substantial amount of progress has been made on thermal modeling of both the Moon and asteroids, and a number of VORTICES researchers, including Howell, Hayne and their students, presented their results at the Thermal Modeling for Planetary Surfaces (TherMoPs) meeting in Budapest in February, 2019.

Howell et al. performed thermophysical modeling of NEAs using the model SHERMAN (Howell et al. 2018, Magri et al. 2018) of (101955) Bennu, Spitzer data from 2012, and VORTICES support. Results were presented at TherMoPs, which showed a phase lag between the thermal and visible observations consistent with a thermal inertia of 310 (SI units). This value also agrees with the spacecraft measurements by Della Giustina and Emery et al. (2019). A comparison of surface roughness measurements using two different formulations in common use (Howell et al. 2018 and Rozitis and Green 2012) finds they differ most at high roughness values for the same physical crater description.

Thermal modeling of NEAs 433 Eros by Mary Hinkle, graduate student at UCF was jointly supported by VORTICES and CLASS (UCF). Mary presented this work at TherMoPS III and at the EPSC/DPS joint meeting in Geneva, Switzerland in 2019, and was first author on “The Global Thermophysical Properties of (433) Eros,” paper submitted to Icarus in September, 2019. This paper presents results of the thermal properties of Eros measured during 18 nights of near-IR spectroscopy from the NASA IRTF from 2009-2019, and finds that a thermal inertia of 125 ± 25 J m^{-2} K^{-1} $s^{-1/2}$ and a roughness crater fraction of 0.35 ± 0.05 fit data from 18 spectra at the 1σ level, but does not fit the remaining 7 spectra. This suggests that Eros’s thermal properties vary over its surface, which has important implications for linking remote sensing data to spacecraft measurements of the physical properties of near-Earth asteroids. This paper is currently under review. Figure 5 illustrates some of the results.

Richardson used SSERVI funding to develop IDL software that performs thermal corrections to asteroid reflectance spectra in the vicinity of 3 μm in cases where the full SHERMAN model is not justified (for instance, for objects with no published shape model). This IDL code is an improvement/retranslation of earlier IDL codes to use newer techniques for thermal corrections (like the Near-Earth Asteroid Thermal Model or NEATM: Harris 2002). The inputs to the software are: an uncorrected asteroid spectrum, an option to select either the Standard Thermal Model (STM) or NEATM to calculate the expected thermal emission from the asteroid, the parameters required by the STM or the NEATM, and options to enable/disable the use of four different methods to correct the input spectrum. Thermal correction of the asteroid spectra is

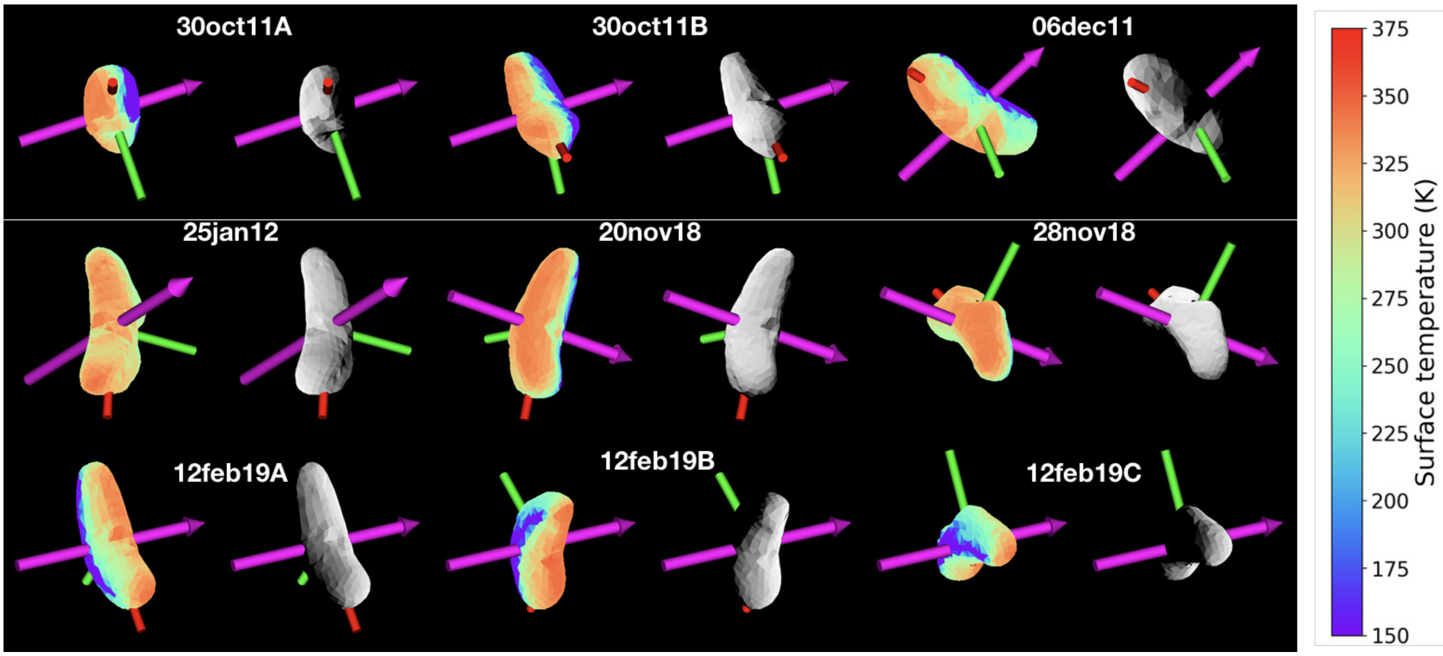


Figure 5. Plane-of-sky views of Eros from the observer's perspective at the mid-time of a subset of Eros measurements. Two images are shown for each observation: the rainbow image is a temperature map with red indicating the hottest temperatures and purple the coldest (scale to the right of the figure), the greyscale image shows the Sun's illumination in the optical regime. The magenta arrow is the rotation axis; the other two principal axes are the red and green bars. Models with thermal inertia in the range 100-150 J m^{-2} K^{-1} $s^{-1/2}$ and surface roughness of 30-40% fit all these observations at the 1σ level.

amongst the initial steps in constructing a small-body taxonomy from 3 μm data (section 1.2.4).

Hayne and his students have made substantial improvements to the "heat1d" planetary thermal modeling code (https://github.com/phayne/heat1d). The Python version of the code is now installable from the command line, using simply 'pip install heat1d.' Former undergraduate Tyler Horvath (now a UCLA grad student), developed thermal and illumination models of lunar caves and is currently preparing them for submission to Geophysical Research Letters.

1.2.5 Asteroid Taxonomy via Machine Learning

Chamberlain and Rivkin have begun to explore different machine learning algorithms and how they may be used to best create a taxonomy of materials in the 3-μm region. To begin our familiarization with the machine learning algorithms that would be most appropriate for our study, they have used the Eight-Color Asteroid Survey data along with the K-Means machine learning algorithm, a part of Pythons scikit-learn library. As the most recent asteroid taxonomies use three "complexes" of asteroid spectra, we decided to process the mean colors of each asteroid using the K-Means machine learning algorithm set to identify three clusters. The results generally find clusters of C-Type and S- Type asteroids, as they are overwhelmingly the most numerous asteroids in those clusters respectively. The third cluster shows that D-Type asteroids are the most numerous; however, an argument could be made this cluster is primarily composed of X-Type asteroids as E, M, and P types are spectrally indistinguishable in the eight-color asteroid survey (and collectively known as the "X asteroids"), and the sum of their contributions is greater than the number of D-Type asteroids in this cluster. In any case, these initial results generally reproduce the membership of the three main complexes: C, S, and X. Further work will expand from these datasets to asteroid spectra in the 3-μm region.

1.3 Regolith Creation and Evolution

Ramesh and his students conducted simulations of the dynamic behavior of geophysical materials for the DART mission impact. Specifically, they investigated the effect of different shape functions in the numerical scheme and impactor properties (basalt vs aluminum) within the Uintah material point method (MPM). Results from these simulations were presented at poster sessions at LPSC

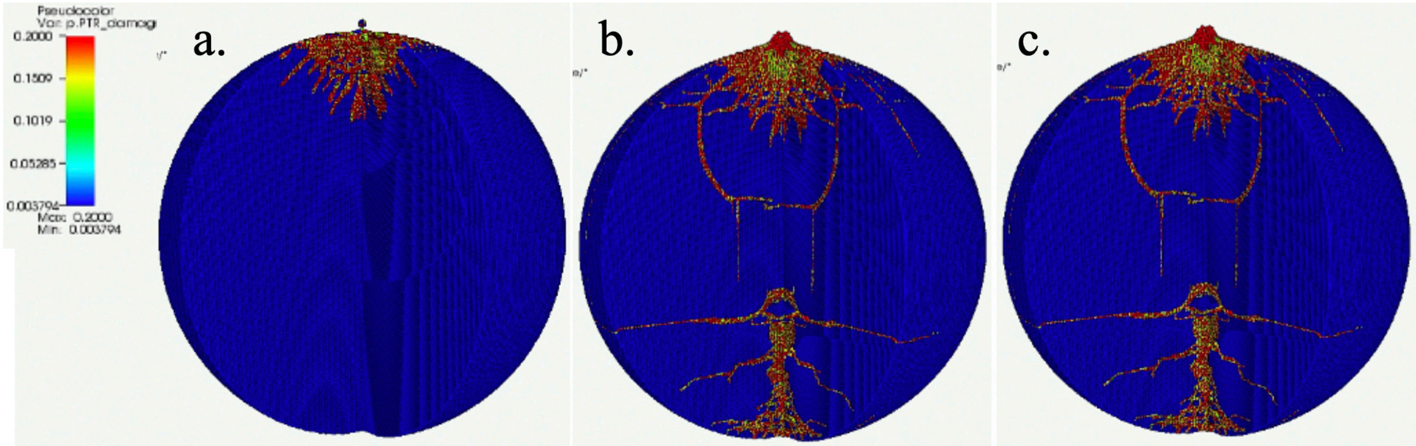


Figure 6: Impact snapshots at (a) 10ms (b) 90ms (c) 230ms for simulations performed using CPTI shape functions in MPM. Impactor trajectory is along the north pole. PTR_damage value of 0.2 (red) represents fragmented material; dark blue represents undamaged material. Damage accrues at both poles.

and the Planetary Defense Conference. They also have been working towards improving the convergence of the code to handle a simulation of the scale of the DART mission, after certain limitations were uncovered in the previous simulation runs. Efforts focused on including size effects and improving the physics incorporated in the code to better predict outcomes at large scales. Such an effort, however, hinges on the development of a refined micro-mechanics based analytical model for predicting the strength of rocks under high and very-high strain rates. Consequently, they have been working towards developing such a framework that incorporates the stochasticity of the microstructural features in greater detail and thereby, captures the coupling of size and rate effects in rocks.

Greenhagen continued his focus in the area of epiregolith thermal gradients. The recent focus of this work was identifying the optimal laboratory environment conditions to match remote sensing data (ground truthing) and using a combination of simulated lunar environment experiments on returned Apollo soils and Diviner Lunar Radiometer data analysis. Preliminary findings from this work were presented at the 2019 European Lunar Symposium and 2019 NASA Exploration Science Forum, which strongly supported using lower temperatures in our laboratory experiments than has been attempted previously. New measurements are in better agreement with orbital observations. This work also attracted the attention of the exospheric community and Greenhagen will attend and support the book-writing duties for an ISSI workshop in early 2020, incorporating surface temperatures and epiregolith thermal gradients into our understanding of Solar System exospheric processes.

Cahill, in cooperation with Banks and Watkins of the TREX team, have begun a comparison using multiple data sets (i.e., Optical Maturity Index (OMAT), LROC photometry) to analyze the surfaces surrounding lobate scarps and other select tectonic structures interpreted to have been recently active (i.e., some wrinkle ridges, small-scale graben). Their goal is to understand the characteristics of surface and near-surface materials that have been disturbed by ground motion from seismic slip events during scarp formation, and assess whether they might inform and benefit future exploration. Our investigations aim to bear on issues relating to ongoing scarp-related seismic processes, the grain size and nature of near-surface regolith, the rate of soil maturation, and if/how these characteristics differ regionally. These results would thus be of use toward identifying additional areas of relatively recently disturbed or exposed surfaces that might also serve as strategic locations for future exploration.

1.4 Community Engagement and Service, Including Mission Concepts

The VORTICES team included many members involved in the lunar and small bodies community at large. One of the major efforts over the past year included the Planetary Mission Concept Studies, proposals solicited by NASA to prepare for the Decadal Survey. VORTICES members were involved in several proposed and selected studies. VORTICES is supporting follow-up work for some concepts that show particular promise but were not selected: Greenhagen will produce a manuscript regarding the Moscoviense Basin as a landing site for a long-duration lunar rover to be submitted to a special issue in 2020. The genesis of this work was a VORTICES-supported presentation that he gave at the Lunar Science from Landed Missions workshop in 2018, which led to the science questions for a PMCS proposal. Other, similar papers for the same special issue will be led by Dave Blewett and Dana Hurley on roving in permanently shadowed regions and mission concepts to lunar swirls.

Building on the research done under SSERVI, Klima joined, as Deputy PI, a SIMPLEX mission team to perform targeted measurements of the lunar surface to investigate the form, distribution, and migration of water/OH on the Moon. This mission, Lunar Trailblazer, was selected for Phase A/B study and is proceeding towards a preliminary design review in summer 2020. **The research supported by SSERVI (and NLSI) over the past decade has been critical in the development of this mission and the formulation of targeted research objectives that can be addressed in a smallsat mission category.**

In addition, VORTICES members attended meetings of importance to the larger community. Due to limited space, we note only that PI Rivkin attended the Women in Space conference in Scottsdale, and Co-I Stickle attended the ESA Space Mining Summit and ESA ISRU workshop in Luxembourg, participating in breakout sessions identifying prospecting needs and techniques for lunar resources, and meeting with representatives from lunar exploration and mining companies to discuss potential future collaborations.

2. VORTICES Inter-team and International Collaborations

2.1 Inter-team Collaborations

VORTICES team members continue to collaborate regularly with scientists throughout the SSERVI program. These include active projects with members of DREAM2, TREX, FINESSE, CLSE, SEEED, IMPACT, ESPRESSO, RIS4E, REVEALS, CLASS and ICE FIVE-O, several of which are described in more detail below. The VORTICES team remains eager to collaborate and willing to provide laboratory support to both other SSERVI nodes as well as members of the planetary community through the last year of our funding as a SSERVI team.

Team members Hurley, Zimmerman, and Prem have continued inter-team research on exosphere modeling and volatile transport between the VORTICES and DREAM2 teams. Team member Matiella Novak is currently working on a project with the FINESSE team that involves using Virtual Reality field studies to enable analog research of planetary surfaces. Our science focuses on analyzing self-secondary impact features at Kings Bowl, Idaho (in a VR environment), as an analog for self-secondary impact features within impact melt ponds on the Moon.

Team members Klima, Greenhagen, and intern Jordan Bretzfelder continue to coordinate with Dan Moriarty and Noah Petro (RIS^{4}E team) on linking Diviner and M3 data to examine the materials excavated by the Apollo basin. Klima has also been working with Donaldson-Hanna on the CLASS team and Carle Pieters on the SEEED team to identify critical targets to examine with the Lunar Trailblazer mission. Together, VORTICES and CLASS have supported a student working with team member Howell at UCF.

Team members Hibbitts has continued close collaborations measuring and modeling volatile transport with Thom Orlando and the REVEALS team, as well as laboratory investigations with Stockstill-Cahill and others on the TREX team. These laboratory investigations include additional measurements examining water in nominally ahydrous minerals with team members Klima and Rivkin. This year also included several other strong collaborations with the TREX team. The presence of many TREX team members in the vicinity of APL has led to the use of VORTICES space for TREX meetings, including cross-team meetings. Team member Cahill continued working with Banks and Watkins on the TREX team to investigate purportedly young lobate scarps on the surface of the Moon. Several team members (Hurley, Greenhagen, Hayne and Cahill) worked with Hendrix (TREX) on a project on FUV-determined hydration with varying Diviner TIR-determined temperature. This paper was published in GRL in 2019.

2.2 International Collaborations

VORTICES members collaborate regularly with international colleagues and support meetings with SSERVI partners overseas. This year we had several team members present at the European Lunar Symposium in Manchester, the European Planetary Science Congress/ Division of Planetary Sciences joint meeting in Geneva, and the Thermal Modeling for Planetary Surfaces (TherMoPs) meeting in Budapest in February, 2019. Ongoing European collaborations include small bodies research work with Marco Delbo of Observatoire Cote d'Azur, Patrick Michel of OCA, and Guy Libourel of Nice and lunar, small bodies, instrument development and laboratory research with Neil Bowles, Tristram Warren, and Kerri Donaldson Hanna at Oxford University in the UK. Deputy PI Klima also served on the Ph.D. thesis committee for Mélissa Martinot at the VU University Amsterdam, the Netherlands, and is a member of a selected ISSI project to investigate space weathering throughout the Solar System led by Francesca Zambon at INAF. Rivkin has continued supporting international meetings about asteroid resources and planetary defense, both of which have significant international interest. VORTICES members also actively collaborate with colleagues in Asia, including Junichi Haruyama, Hiroyuki Sato, and others at JAXA as well as Seiji Sugita at the University of Tokyo.

3. Public Engagement Report

Sixth year Public and Student Engagement activities built upon past SSERVI partnerships and leveraging resources to continue implementing a program that targets a diverse audience. Our activities engaged students, educators and the general public with SSERVI and VORTICES science and engineering themes.

3.1 Student Engagement

Student engagement activities included visits to several schools in the Anne Arundel County STEM Magnet program. This included science presentations for the South River High School Girls STEM Club, and the 4th grade class at Central Elementary School. Additionally, we participated in a Careers in Space Science session at the 2019 Society for the Advancement of Chicanos/ Hispanics and Native Americans in the Sciences (SACNAS) Diversity in STEM Conference. Over 100 students were directly engaged with VORTICES scientists throughout the year. For another student engagement activity in the summer, about 50 students participating in the Maryland Summer Center for Gifted and Talented Students Space Camp at the Applied Physics Laboratory saw a Magic Planet presentation. During this presentation, students learned about planetary mission planning, how scientists and engineers work together to determine Solar System exploration science questions, as well as how they build mission spacecraft to explore and answer those questions.

Klima has continued to work closely with international partners and to share her research broadly through outreach and other events. This year she served on the defense committee for Melissa Martinot, a student of Wim van Westrenen of the Netherlands SSERVI team. In addition, Klima is a member of a recently selected ISSI team to study space weathering on different bodies in the Solar System, led by Francesca Zambon at INAF. She was invited to present a talk for the Water in the Universe workshop at the American Chemical Society meeting, where she provided an overview of the work that VORTICES and other SSERVI teams have done to advance our understanding of the distribution and origin of water on different bodies throughout our Solar System. She also presented similar work at the educators institute held at APL in the spring, as well as at the Space Science Summer school for high school students in Boulder, CO.

3.2 Engagement Institutes

3.2.1 Workshops for Undergraduate and Graduate Students

We facilitated two workshops for undergraduate and graduate students on submitting competitive internship applications. The first was at the 2019 SACNAS conference, and the second was a one-hour webinar in December. Feedback from these workshops showed that they were very useful and students applying for internships are seeking out resources to make their applications more successful. A separate report on the SACNAS effort was prepared and submitted to SSERVI HQ for use as a nugget. Lastly, a VORTICES scientist participated in the Apollo 11 Mission’s 50th Anniversary events at the Maryland Science Center, giving a presentation on the past, present and future of lunar exploration.

3.2.2 Planetary Scientist Engagement Institute

VORTICES also held a Planetary Scientists Public Engagement Institute with scientists attending the 2019 Lunar and Planetary Sciences Conference (Figure 7). The goal of the program was to share content that included common Solar System misconceptions, techniques for addressing controversial topics, simple activities and demonstrations for engaging audiences, and connecting with local museums and astronomy clubs. Twenty-three scientists at various stages of their careers (professional, graduate students and post-docs) from across the US attended the 2-day Institute at LPI. The institute included interactive activities and demonstrations, and extensive time devoted to discussion to allow participants to share their experiences and insights. SSERVI education and outreach professionals gave presentations on web-based tools to help with engagement and sharing science.

Figure 7: Scientists gather at the Public Engagement Institute.

4. Student/Early Career Participation

Undergraduate Students

1. Lalliet Vila Rodriguez – ATLAS summer intern, spectral modeling work

Graduate Students

1. Sakshi Braroo, Johns Hopkins University, Impact modeling
2. Kiana McFadden, University of Arizona, small bodies
3. Mary Hinkle, University of Central Florida, small bodies (CLASS-funded but advisor Howell supported by VORTICES)

Postdoctoral Fellows

1. Pavarthy Prem, Johns Hopkins Applied Physics Laboratory, Thermal and volatile modeling (VORTICES, TREX and DREAM2 collaborations)
2. Jack Wilson, Johns Hopkins Applied Physics Laboratory, Thermal and volatile modeling
3. Matthew Richardson, Planetary Science Institute, Asteroid thermal modeling and machine learning

Former Undergraduates now in Graduate School

1. Jordan Bretzfelder, now at UCLA
2. Tyler Horvath, now at UCLA

New Faculty Members

1. Charles El Mir, University of Saint Louis, Madrid, Spain (former SSERVI-supported student, but as a non-US person he is no longer supported by SSERVI

5. Current Mission Involvement

1. DART, Andy Rivkin, Investigation Team Lead
2. DART, A. Stickle, Co-I
3. LRO / LROC, J. Plescia, Co-I, geology
4. LRO/Mini-RF, L. Carter, Participating Scientist
5. LRO/Mini-RF, A. Matiella Novak, Co-I
6. LRO/Mini-RF, J. Gillis-Davis, Co-I
7. LRO/LAMP and Mini-RF, J. Cahill, Participating Scientist and Co-I
8. LRO/LAMP, D. Hurley, Co-I
9. LRO/Diviner, B. Greenhagen, Deputy PI
10. LRO/Diviner, P. Hayne, Co-I
11. LRO/Diviner, M. Siegler, Co-I
12. LRO/Diviner, R. Klima, Team Member
13. LRO/Mini-RF and LAMP, A. Stickle, Science Team Member
14. MRO/CRISM, A. Matiella Novak, Team Member
15. OSIRIS-REx, E. Howell, Spectroscopy Collaborator
16. Europa Clipper, R. Klima, Project Staff Scientist
17. New Horizons/LORRI, A. Rivkin, Team member
18. Psyche/GRNS, D. Lawrence, Instrument PI
19. MMX/MEGANE, D. Lawrence, Instrument PI
20. NEA Scout, A. Rivkin, Co-I
21. Lunar Flashlight, B. Greenhagen, Co-I
22. Lunar Flashlight, P. Hayne, Co-I
23. DESTINY+, A. Rivkin, Collaborator
24. Lunar Trailblazer, K. Klima, DPI

Exploration Science Pathfinder Research for Enhancing SS Observations (ESPRESSO)

Alex Parker
Southwest Research Institute in Boulder, CO

CAN 2 TEAM

1 ESPRESSO Team Report

In 2019, the Project ESPRESSO team continued to make substantial progress on all of its major programs, including development of miniaturized sensors for lunar and asteroid deployment and field testing of potential handheld instrumentation. The team also started a new Accessible Exploration Initiative to explore strategies to improve accessibility of planetary exploration programs.

1.1 Magnetic Sampling and Anchoring Technologies

1.1.1 Magnetic Anchoring for Seismic Sensors

Anchoring small landed sensor packages to the surfaces of low-g bodies represents a substantial technical challenge, as epitomized by the multi-km "bounce" of ESA's Philae lander. Active anchoring systems (e.g., harpoons) must contend with an enormous range of possible surface material strengths and cohesion properties, while passive settling under gravity results in extremely tenuous contact with surface material. To achieve efficient acoustic coupling with asteroid interiors for seismic studies, a new approach was merited. Project ESPRESSO team members constructed a gravity-reduction pendulum system to provide extremely low but tunable g-levels over small displacements in a horizontal plane. This system allowed direct comparison of anchoring methods for seismic instruments. A brick of JAXA-developed Phobos regolith simulant was placed parallel to the pendulum and driven by an acoustic transducer to simulate a seismic signal. An IMU placed on the pendulum measured the signal transferred from the regolith into the pendulum through a passive contact patch under varying gravity loads, and through a magnetized contact patch under the same gravity loads. Under Phobos-like gravity conditions, a 50 Hz seismic signal was found to be conducted with vastly greater efficiency through the magnetized contact patch, delivering a 34 dB signal gain (see Figure 1).

> Project ESPRESSO experiments demonstrated that magnetic anchoring can improve seismic sensor coupling to low-g surfaces by many orders of magnitude.

1.1.2 Femtosatellite-scale Seismic Sensor Mote

To further develop the concept of a magnetically-anchored asteroid seismic network, team members developed, implemented, and tested a fully-functional prototype magnetically-anchored seismic sensor mote (see Figure 1). The motes include a C&DH computer, power-management system, battery, solar arrays, a 3-axis 2000 Hz IMU, and a long-range radio transceiver. They are assembled in a "caltrop" configuration, with four tetrahedrally-arranged magnetized feet extended on shock-absorber legs; this arrangement ensures that no matter the orientation at landing, three of four feet will come in contact with the surface and provide magnetic anchoring. This arrangement is sufficient to anchor the mote to a vertical wall of simulated Phobos regolith even under laboratory 1g conditions. The entire magnetically-anchored seismic sensor mote has a mass of just 48 grams, yet can run on battery power alone for approximately one week and can transmit data at 250 kbps to another sensor mote in its network at a range of up to 500 meters. Mote-to-parent spacecraft data link range can be made far greater with a lower-noise receiver and a high-gain antenna.

At under 100 grams, these sensor motes fall into the

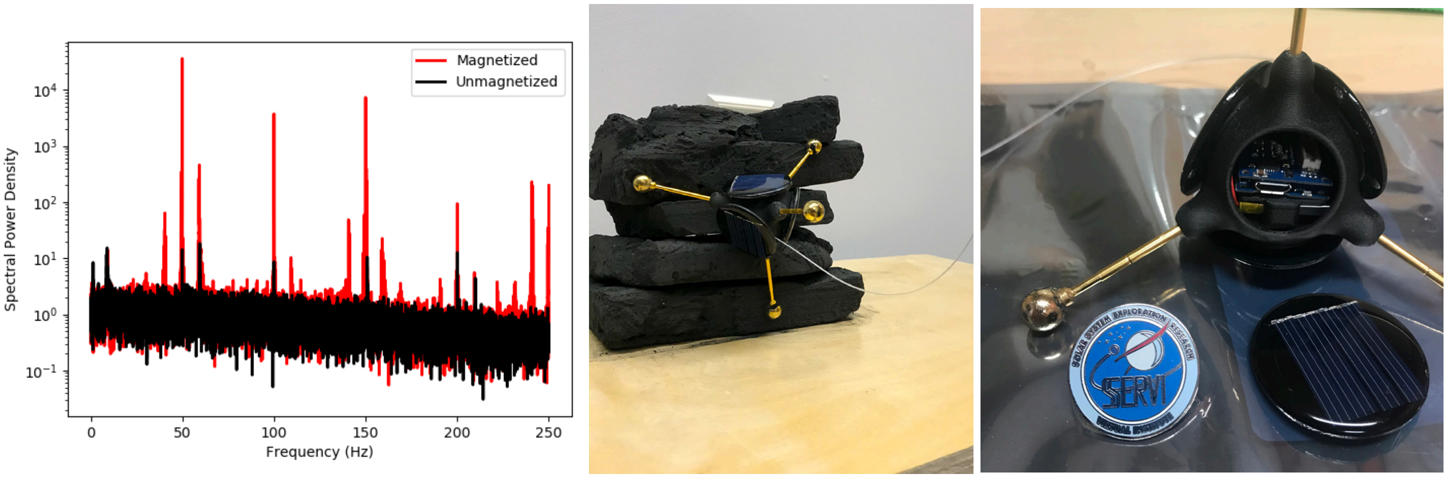


Figure 1, Left: Example acoustic power spectrum recovered by an IMU in passive contact with a Phobos regolith simulant under Phobos-like gravity conditions (black) and with magnetic anchoring (red), showing 34 dB gain at the 50 Hz driven signal. Middle: The fully-functional 48-gram seismic sensor mote, magnetically anchored to an irregular vertical wall of Phobos regolith simulant. Caltrop shape enables three of four legs to contact surface in spite of irregularity. Solar panels and whip antenna also shown. Right: Interior of the seismic sensor mote, showing the tightly-packed electronics, which include the C&DH computer, battery and PMU, instrument, and radio transceiver. SSERVI pin is 25 mm in diameter, for scale.

The entire magnetically-anchored seismic sensor mote has a mass of just 48 grams.

"femtosatellite" regime. Hundreds could be deployed from a parent spacecraft and allowed to passively fall to the surface of a target asteroid, forming both a dense seismic network and a resilient data-distributing mesh network to relay refined seismic information back to the parent spacecraft. Even with relatively limited unit survival times, a program to re-deploy replacements from the parent spacecraft at sporadic intervals could maintain the integrity of the seismic network and the mesh network for extended mission durations. Such a mission architecture could enable revolutionary structural studies of asteroids and low-g moons such as Phobos; deployment in advance of a planned impact (e.g., the DART mission) would enable active tomography of interior structures, while deployment in advance of planetary flybys (e.g., the ultra-close Earth flyby of the asteroid Apophis in April 2029) could reveal how tidal torques alter the interior structure of asteroids during planetary encounters.

Project ESPRESSO will continue to refine and test these seismic motes, including planned thermal-vac testing, development of a scalable transport and deployment system, and demonstration of deployment and anchoring during reduced-gravity flights in April 2020. Further development of a ground-spike version for rapid human deployment of dense lunar seismic networks will begin in early 2020 as well.

1.1.3 "Clockwork Starfish" Magnetic Regolith Sampler Demonstrator

In addition to magnetic anchoring, Project ESPRESSO efforts in 2018 demonstrated that magnetic grapples hold great potential for low-g sample collection. In 2019, further development of the magnetic regolith sampling concept resulted in a NASA Flight Opportunities Program award to fly a Project ESPRESSO sampling demonstrator within the BORE-II vacuum chambers on a Blue Origin New Sheppard rocket in mid-2020. This sampling demonstrator is a picosatellite-scale free-flying mechanism that will impact a simulated asteroid surface under microgravity in vacuum, collect regolith on its magnetized outer surface, and then turn itself inside-out. This "eversion" process is a bit of biomimicry inspired by the mechanism by which starfish consume food; thus the moniker Clockwork Starfish. Once everted, the Clockwork Starfish has confined any captured regolith in its new interior, and its new exterior is magnetically shielded to prevent any further accumulation of regolith. In a mission environment, this eversion would also expose cold gas thruster ports to enable the Clockwork Starfish to hop from

Figure 2: CAD render of the Project ESPRESSO-developed Mk.III Clockwork Starfish magnetic regolith sampling demonstrator that will fly aboard a Blue Origin New Sheppard suborbital rocket in mid-2020.

waiting parent spacecraft. Such a mission architecture enables multi-point, multi-target asteroid sample return without ever committing the parent spacecraft to a risky touch-and-go maneuver. Such missions are a natural follow on to the current generation of single-target, single- or dual-site sample return missions.

Project ESPRESSO team members have substantially refined the Clockwork Starfish design and implemented a Mk.III prototype (illustrated in Figure 2) since selection in September, 2019. The eversion is achieved through a low-power, highly-robust reel-out mechanism, and the arrangement of the magnetic panels provide a locking force once the eversion is complete. Jams between the petals are cleared by three shake motors located on the petal faces. Total system mass of the Blue Origin demonstrator is 175 grams; future conceptual flight versions fit within the envelope of a 1U cubesat.

1.2 Instrumented Impactors for Remote Terrain Stability Assessment

The Project ESPRESSO instrumented impactors team has been steadily progressing on both theoretical and technical fronts. The long-term goal of the instrumented impactor effort is to develop a tiny disposable impact probe that can use its deceleration profile to return terramechanical information about a terrain before committing a human or robot to a potentially-risky traverse. As such, miniaturization has been paramount. As of the end of 2019, the team has reduced the volume of its 40 mm Gen. III impact probes by a factor of 15 compared to Gen. I, while simultaneously doubling its peak performance (up to an IMU sampling rate of 2000 Hz at a transmission range of half a kilometer). Figure 3 illustrates the evolution of the impact probe form factor; field deployments will begin in 2020.

Project ESPRESSO's impactor team have also conducted a series of laboratory drop experiments chasing after the utility of edge affects - particularly the affect of the hard

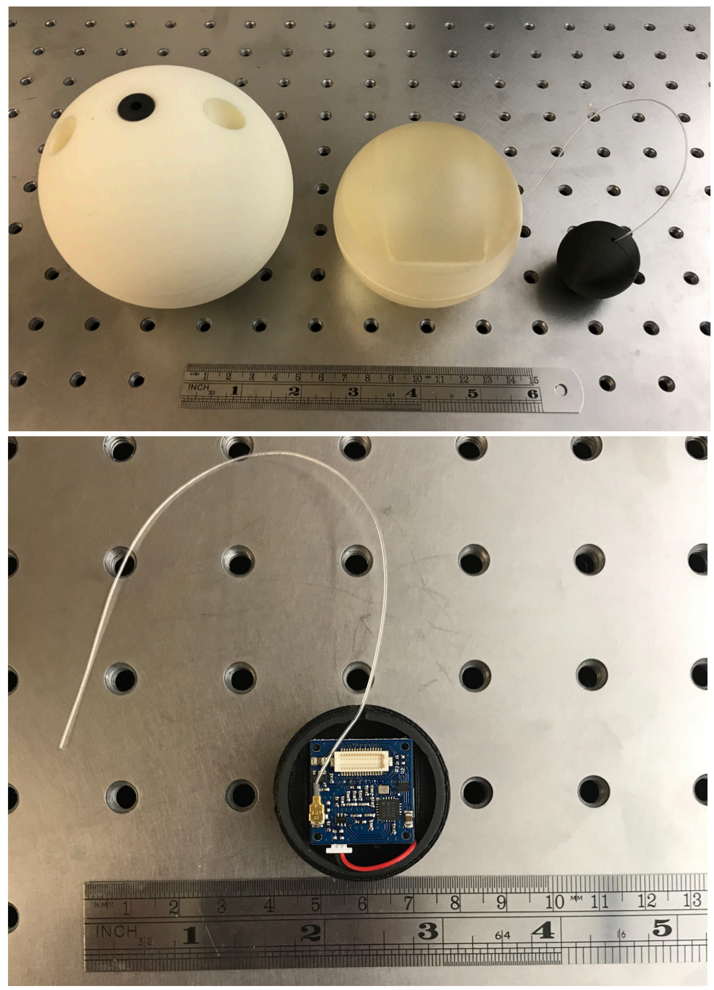


Figure 3: Top: Evolution of the instrumented impactor envelope. Leftmost sphere is the 100 mm Gen I impactor developed in the first months of Project ESPRESSO. Middle 80mm Gen II impactor was developed in late year 2. Rightmost sphere is the current 40 mm Gen III impactor; Bottom panel shows internal electronic pack-aging, including battery, high-speed IMU, and long-range radio transceiver.

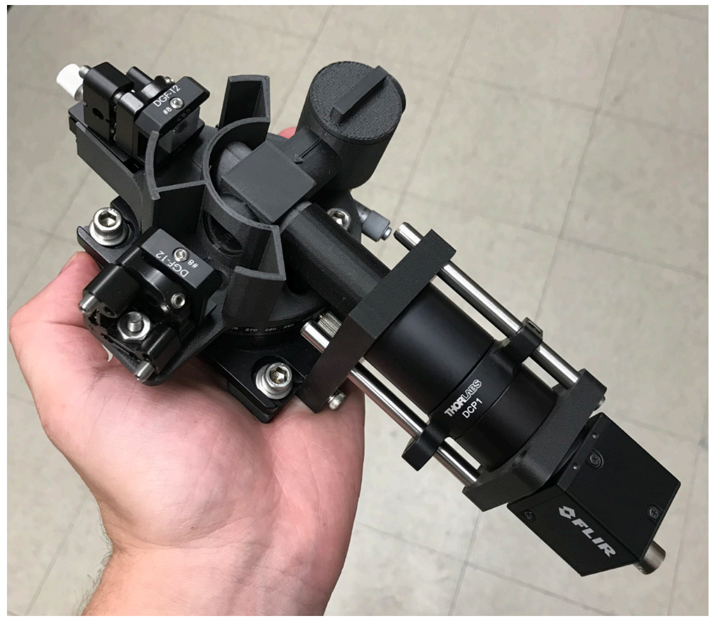
The impact probes have shrunk 15 times in volume while doubling performance.

bottom of the target bed container to represent an end member case of a stratified regolith. There exist in the literature numerous force laws for the force profile felt by the impactor during a low speed impact into granular materials. These exist for ideal scenarios with no container edges and an infinitely deep container. The current suite of experiments measure deviations from the idealized force law as the bed depth is decreased, and determine how these non-idealities may be exploited to measure regolith stratification in lunar and asteroid terrains. A number of these experiments were conducted with high-density Airsoft pellets as the target material, which are useful end members because they can be modeled one-to-one in modern granular mechanics codes. Given the large size of the pellets (D=6mm) the drops provide particularly grainy outcomes. The faster and more accurate accelerometers in the Generation III impactors will better resolve these grain-scale effects and eliminate some need for averaging; further, their vastly-reduced size will enable smaller beds and smaller grain sizes to be tested. These drop experiments will be repeated in lunar and asteroid-like gravity conditions during our 2020 flight campaigns.

1.3 Active Spectroscopy Instrumentation Development

1.3.1 Tuneable Spatial Heterodyne Raman Spectrometer

As part of Project ESPRESSO's long-term goal of enabling extreme-range laser-activated spectroscopy, ultra-high throughput, high-resolution, high-etendue spectrometers are required. The spatial heterodyne spectrometer is a device that meets these needs, but they are notoriously difficult to construct and calibrate. Project ESPRESSO team members have implemented a new spatial heterodyne spectrometer design optimized for Raman and LIBS applications where extremely high spectral resolution is required (e.g., optical measurement of D/H in LIBS spectra) but where a broad range of accessible wavelengths is also desired. The Project ESPRESSO spatial heterodyne spectrometer is tunable with only one mechanical degree of freedom; optical components rotate around a common axis on a single rotation stage, enabling a deterministic central wavelength sweep with no subsequent calibration or alignment required. In spite of being an interferometric instrument, the design is so optically tolerant that the main metering structure was constructed out of *3D printed plastic parts* and still delivered stable R~3000 performance with a tunable central wavelength. A sulfur Raman spectrum collected by this plastic interferometer is illustrated in Figure 4.



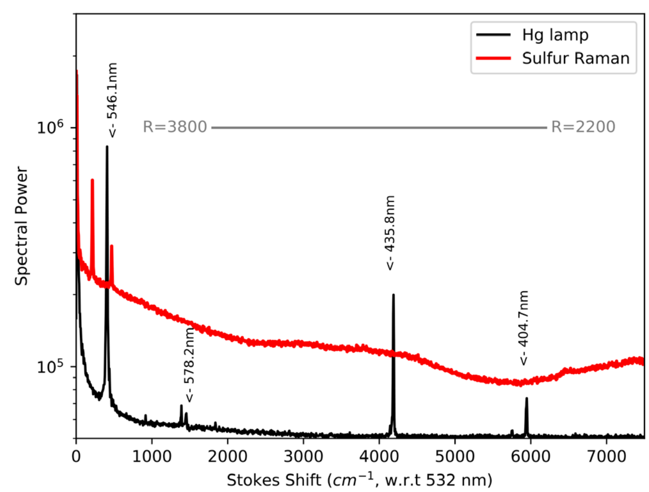


Figure 4: Top: Compact tunable spatial heterodyne spectrometer developed by Project ESPRESSO team members. The micrometer stage visible near image center shifts the central wavelength with no subsequent tuning or calibration required. Bottom: A Raman spectrum of Sulfur acquired with this spectrometer, and the spectrum of an Hg calibration lamp.

1.3.2 Acoustic Levitation for Trapping Regolith Fines in Free Space

One of the chief challenges identified by Project ESPRESSO's Grain Velocimetry and Tomography Analysis System (GraVeTAS) team in developing laser velocimetry and tomography tools lay in calibration; repeatably passing micron-scale particles with known properties through controlled locations within an instrument volume at controlled speeds was persistently foiled by electrostatic forces and stray drafts blowing the particles away. The team found an unlikely but effective solution: acoustic levitation. Two low-cost arrays of ultrasonic transducers create stable pressure fields that can trap particles in free space at controlled locations, and the patterns of these pressure fields can be modulated permitting control of the particle motion. The team implemented an acoustic levitation array (Figure 5) to trap calibration particles within the volume of regard of the GraVeTAS instrument to enable detailed calibration of the instrument performance for a variety of particle sizes and shapes.

1.3.3 Ultra-Low Cost Handheld Fluorimeter for Mineralogy

Project ESPRESSO team members Parker & Soto co-mentored Leafia Sheraden Cox, a UNAVO RECESS undergraduate intern in the summer of 2019. During the short duration of the internship, this trio designed, implemented, calibrated, and field-tested a novel ultra-low cost handheld reflectance spectrometer and fluorimeter. The instrument employed a set of spectrally-filtered photodiodes and carried white light, UVA, and UVC illumination sources. It also had substantial onboard processing power and ran a custom regression algorithm to identify mineral mixtures in a given calibration set; the instrument was calibrated using mineral samples at the Denver Museum of Nature and Science (Figure 6). The instrument was then deployed in the 2019 Project ESPRESSO field campaign at the Palisades Sill lunar analog site. It demonstrated a robust ability to estimate the ratio of plagioclases to pyroxenes exposed on a rock face with integration times of less than 10 seconds. Strong red fluorescence of plagioclase minerals under UVC provides a powerful mineralogical diagnostic for lunar applications with a low cost instrument. The unit cost was under $300 USD and with further refinement is expected to be below $100 USD; Leafia Sheraden Cox

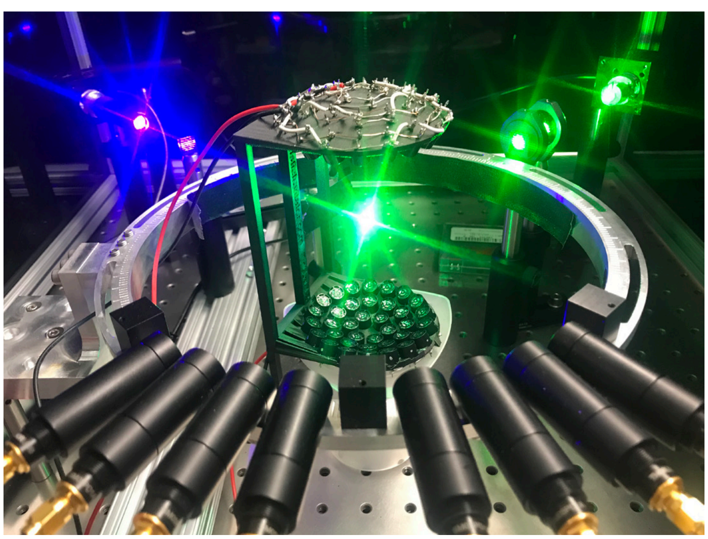


Figure 5: An acoustic levitator (center) locking a 30-micron scale particle (bright source, center) in free space within the field of regard of the GraVeTAS instrument (ring, phodiodes, lasers).

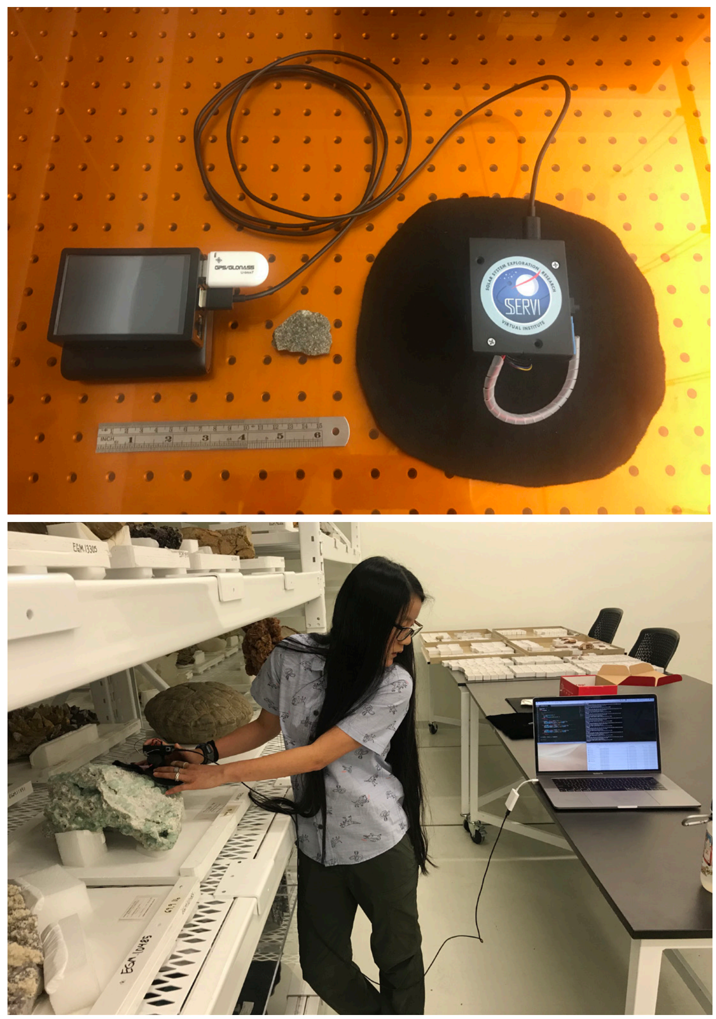


Figure 6: Top panel: Handheld fluorimeter, illustrating data analysis computer, GPS module, and battery (left) and sensor head with integrated light shroud (right). Bottom panel: UNAVCO RECESS undergraduate intern Leafia Sheraden Cox collecting calibration data for the fluorimeter at the Denver Museum of Nature in Science.

> The handheld fluorimeter was designed, assembled, calibrated, and field-tested at a lunar analog site in just two months.

has subsequently undertaken a directed study effort to open-source the instrument design so that it may be used for environmental contamination assessment throughout the world.

1.4 2019 Project ESPRESSO Field Campaigns

In 2019, Project ESPRESSO led its first dedicated lunar analog field campaign to the Palisades Sill in New Jersey, an intrusive diabase dike with well-understood mineralogy, ideal for testing instrument performance in a field setting. The campaign was organized by Project ESPRESSO postdoctoral fellow Dr. Marcella Yant, and the Project ESPRESSO team deployed handheld LIBS, Raman, and fluorimeter instruments. Analysis of the performance of these instruments in the field setting is ongoing; early analysis of the fluorimeter data indicates qualitative agreement with published compositional trends. The campaign also supported graduate students from Brown and Cornell, who deployed instruments from their institutions. This pathfinding field campaign confirmed that the Palisades site is ideal for future lunar analog studies.

Project ESPRESSO team members also deployed to Iceland to field-test a variant of the GraVeTAS instrument designed to track particles entrained in gas or fluid flow. The instrument was deployed in both static and mobile rover-mounted configurations (Figure 7) on the periphery of the Þórisjökull glacier, and monitored basalt fines carried by katabatic winds. This instrument variant may be used in future investigations of rocket exhaust ejecta in the lunar environment.

2. Inter-team/International Collaborations

2.1 Desert Fireball Network

Project ESPRESSO has initiated efforts to deploy a Desert Fireball Network node over Eastern Colorado, and further supported deployment of a new network in New Zealand.

2.2 CAN3 Teams

Project ESPRESSO team members are involved as collaborators in a number of the newly-selected CAN3 SSERVI nodes, including GEODES and RISE-2. In particular, joint field campaigns are planned during the overlap of Project ESPRESSO and the CAN3 teams.

2.3 TREX-led EPO efforts

Project ESPRESSO team members supported the TREX EPO efforts at Boulder County farmers markets.

2.4 JAXA Collaborations

Project ESPRESSO team members continue to be involved in the JAXA MARAUDERS effort to develop micro-landers for lunar polar region exploration, and successfully participated in a stellar occultation campaign to determine the solid-body size of the DESTINY+ mission target Phaethon.

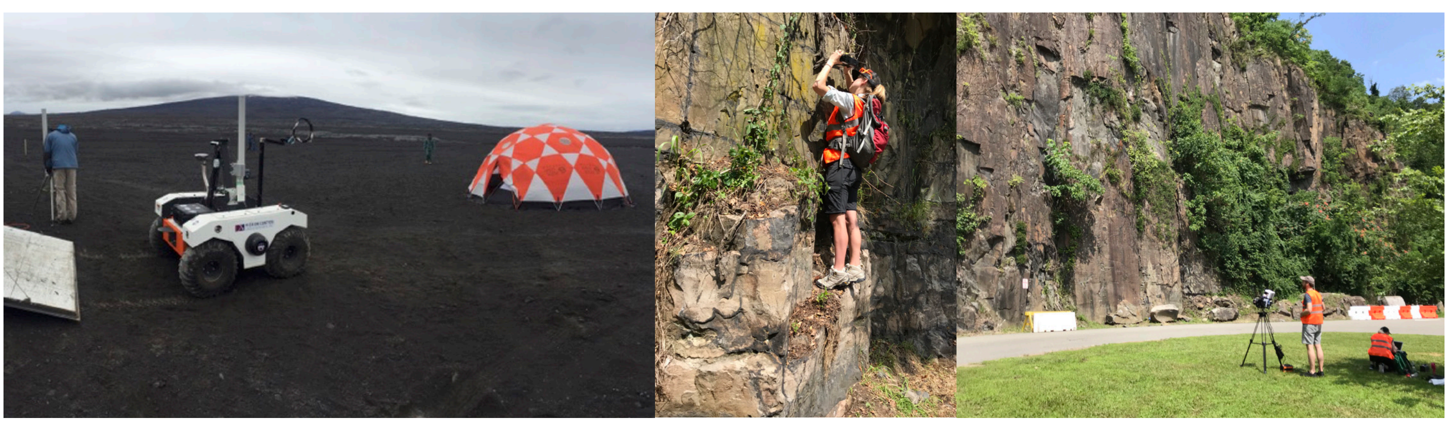


Figure 7: Left panel: GraVeTAS Hura variant deployed on the periphery of the Þórisjökull glacier, Iceland (boom-mounted ring). Middle and right panels: Scenes from the 2019 Project ESPRESSO field campaign at the Palisades Sill, New Jersey, including acquisition of Raman spectra of exposed sill face and acquisition of MastCam-Z engineering model imagery.

3. Public Engagement

Project ESPRESSO's Accessible Exploration Initiative, a proposed education and public outreach augmentation, was approved in mid-2019. Early efforts include the rapid integration of the Tactile Telescope System, which consists of a pair of portable telescopes instrumented with sensitive cameras coupled to both a visual projector and non-visual display methods. These include a thermal swell-paper tactile printer and a novel ultra-low cost haptic interface glove developed by the Project ESPRESSO team. The goal of this system is to enable groups to share interactions with real-time lunar imagery, and to include individuals with visual impairments in the exploration of the Moon. The telescopes have been deployed to community spaces around Boulder, including a New Years Eve 2019 lunar viewing party that drew approximately 40 visitors in spite of freezing temperatures. The system will be further refined and deployed in 2020; the haptic interface will be presented at the 2020 LPSC meeting.

Project ESPRESSO team members also assisted with the TREX-led Boulder County Farmers Market booth, bringing the 2018 reduced gravity vacuum chamber to demonstrate the effects of a space-like environment on familiar materials.

4. Student/Early Career Participation

Undergraduate Students

1. Leafia Sheraden Cox, Wellesley College, Instrument Development.

Worked as a UNAVCO RECESS program summer intern with Project ESPRESSO mentors Parker and Soto to develop and test a portable fluorimeter instrument. Participated in 2019 field campaign and Phaethon occultation campaign. Fluorimeter design and performance presented at 2019 AGU fall meeting. Now conducting a directed study program with co-mentorship from Parker & Soto to further develop and test the fluorimeter technology and release it as an open-source design.

Postdoctoral Fellows

1. Dr. Marcella Yant, Johns Hopkins University, Optical Constants and Analog Field Instruments.

Project ESPRESSO postdoctoral fellow. Led 2019 Palisades field campaign and LIBS/Raman data analysis efforts. Joined 2020 Mini Desert RATS campaign at Mojave Lava Tubes.

In March 2020, Dr. Yant will take a new position as a Planetary Research Scientist at Lockheed Martin in Littleton, CO. The Project ESPRESSO team is delighted to have had Marcella as a postdoc and are excited to see her continue to rise in the field!

New Faculty Members

1. Dr. Alex Parker, Southwest Research Institute, promoted to Principal Scientist.
2. Dr. Keith Nowicki, Southwest Research Institute, promoted to Principal Engineer.
3. Dr. Alejandro Soto, Southwest Research Institute, promoted Senior Research Scientist.

5. Mission Involvement

No Project ESPRESSO team members' flight mission involvement in 2019 was predicated upon previous SSERVI research. However, ongoing Project ESPRESSO experimental efforts complement multiple team members' involvement in OSIRIS-REx (including micrometeoroid ejecta and thermal fracturing ejecta from Bennu-like regolith experiments; team members Walsh and Molaro). The NASA Flight Opportunities Program selection of BORE-II and the Clockwork Starfish demonstrators (team members Durda and Parker) to fly aboard a Blue Origins New Sheppard rocket in 2020 was predicated upon the Project ESPRESSO 2018 reduced-gravity demonstration of magnetic sample collection technology.

6. Awards

- Professor Sarah Hörst, Project ESPRESSO Co-Investigator at Johns Hopkins University, was awarded the 2019 AAS Laboratory Astrophysics Division Early-Career Award.
- Dr. Kelsi Singer, Project ESPRESSO Co-Investigator at the Southwest Research Institute, was awarded the 2019 DPS Urey Prize.

Network for Exploration and Space Science (NESS)

Jack Burns
University of Colorado Boulder, CO

CAN 2 TEAM

1. NESS Team Report

1.1 Surface Telerobotics

1.1.1 Simulations of the Lunar Terrain to Assist in Lander Development

To support the development of an improved virtual reality lunar rover simulator, Co-I Fong collaborates with CU Boulder (SSERVI/NESS postdoc M. Menon) on techniques to improve real-time, photorealistic rendering of the lunar surface. The simulator supports mission studies such as rover-deployed antennas by creating approximate, but plausible visualizations of terrain geometry, regolith appearance, and solar illumination. Future work will include comparison of the CU Boulder virtual reality simulator (which is based on the Unity video game software system) to the NASA Ames lunar surface operations simulator.

1.1.2 Virtual and Augmented Reality Simulations of Robots on the Lunar Surface

Our group (Walker, Menon, Szafir, and Burns) is using game engines, simulators, augmented reality, and virtual reality (VR) technology to enhance interfaces used by scientists and astronauts during robotics missions. Stereoscopic displays built into VR headsets allow users to see with depth through the eyes of a real robot. By passing the dual video streams from a physical camera on a robot to a remotely located human operator, it is as if they were there themselves embodied as the robot. A virtual lunar environment simulator was created within a robust physics engine to provide a platform for evaluating and advancing algorithms that govern low-level robot autonomy and support interactive trade-offs between various levels of supervisory control. In this work we found that state-of-the-art computer vision algorithms, commonly used for autonomous robot localization and mapping, break down and fail to initialize or continuously estimate poses when a scientifically accurate photometric shader is introduced to a terrain model. The virtual environment may enable explorations into the design of new interfaces that support ground control and/or orbital station astronaut operation of surface robots.

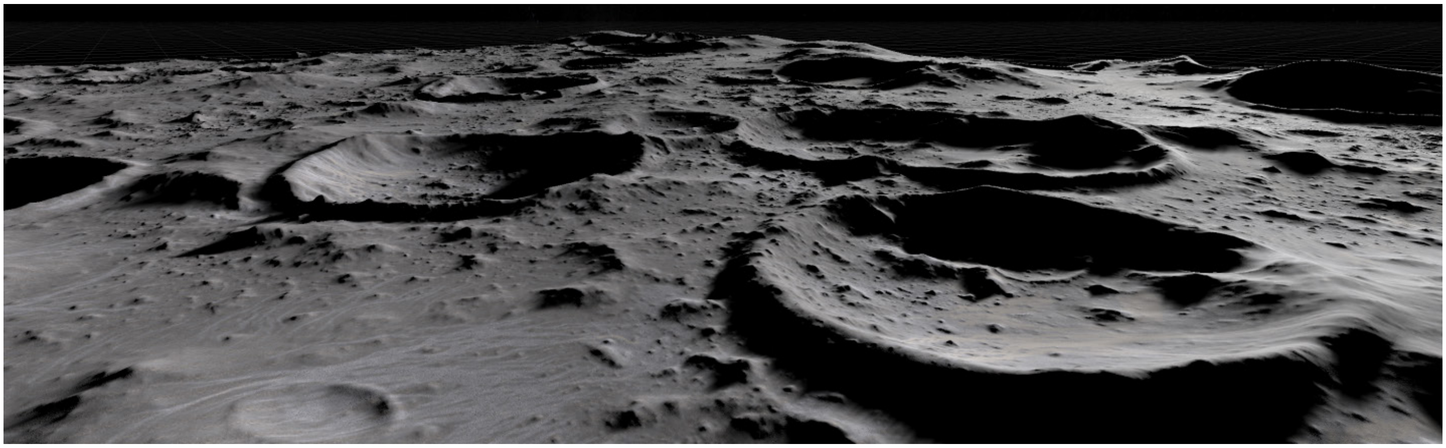


Figure 1: Rendering of the lunar surface from the real-time simulator being developed with photometric models of the Moon's surface.

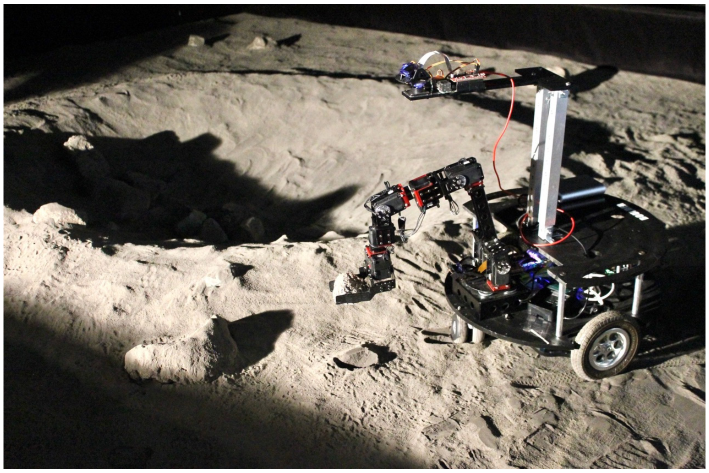


Figure 2: CU-Boulder Armstrong rover with mounted mechanical arm and cameras in the simulated lunar landscape at NASA Ames Research Center.

1.1.3 Assembly of Radio Telescope Components on the Lunar Farside: Experiments Using Laboratory-based Teleoperated Rover and Mechanical Arm

In 2019, the CU Telerobotics Laboratory finalized our Telerobotic Simulation System (TSS). The Lab team included three undergraduate engineering students (Kumar, Bell, Sandoval) and an M.S. aerospace engineering student (Mellinkoff) supervised by P.I. Burns. The TSS enables remote operation of our Armstrong Rover, a commercial off-the-shelf rover with a 6 degrees-of-freedom robotic arm. Two cameras were placed on Armstrong to provide video feedback to the operator. The hardware was supported by a control GUI consisting of video feeds, a real time updating model of the rover, and sliders indicating limits of the arm's movement.

Armstrong and the TSS were used in our most recent experiment designing a methodology that can accurately assess situational awareness and the cognitive load of an operator performing a telerobotic assembly task. As an analog to the FARSIDE mission concept, operators were tasked with assembling, deploying, and powering a small array of three antenna units. Each participant completed the assembly task under two conditions: remote teleoperation of Armstrong and local operation of Armstrong. Performance metrics measured in this experiment showed greater situation awareness and lower cognitive load in the local environment, supported by a 27% increase in the time required to complete the task when operating remotely. Results from this experiment refined our methodology to more accurately assess the human factors associated with telerobotic assembly.

1.2 Hydrogen Cosmology

1.2.1 Instrument Development

The Cosmic Twilight Polarimeter (CTP) concept, led by Co-I Bradley, saw major developments over the past year. While investigating and maturing the instrument stability and calibration of the CTP, we had an undergraduate summer student, Ellie White from Marshall University, help us set up a simple experiment to determine if induced polarization could be observed. This experiment was vital in verifying the basis of the polarimetric approach we are developing for cosmological 21-cm observations with the CTP and the Dark Ages Polarimetry Pathfinder (DAPPER) mission concept. Bordenave and Nhan continued with the development and data analysis from this test instrument.

This simple experiment relied on existing hardware from the Precision Array for Probing the Era of Reionization (PAPER) project and was set up in Green Bank, WV (Figure 3). It consisted of a single crossed-dipole antenna pointed towards zenith along with a wideband balun and a modified amplifier module used by the PAPER project. Although not ideal to detect the actual 21-cm signal, the higher frequency range (120-200 MHz) of the system allowed us to avoid much of the RFI typically found at low frequencies (<100 MHz). Additionally, this set-up also lacks absolute calibration and the system relies entirely on lab measurements of the active RF modules instead. Despite these instrumental shortcomings, White was able to obtain a very repeatable and clean total power measurement of the sky.

Given the good quality of this initial data, we decided to focus our efforts on upgrading the experiment for further study. The back-end of the instrument saw the

Figure 3: Deployed PAPER antenna at Green Bank WV, set-up for zenith pointed drift scans.

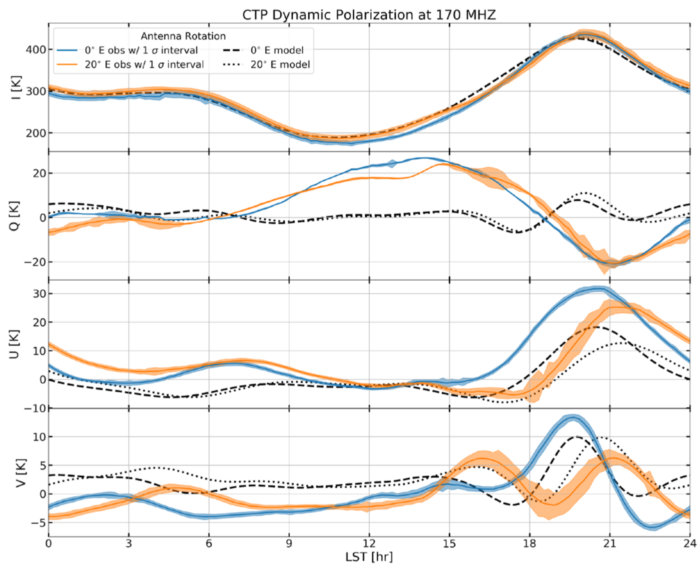


Figure 4: Observed Stokes brightness temperatures and simulations over sidereal time. The colored curves show the observed Stokes brightness temperatures with 1-σ intervals for two configurations: (blue) x-pol aligned with grid north for one week, (orange) x-pol rotated in azimuth by 20 degrees east for two weeks. The black dashed and dotted curves show the simulated brightness temperature for the North and +20 east aligned antenna respectively. Note that the data generally tracks the behavior of the simulations and that the signal remains stable over weeks of observations. The greater deviation in Q Stokes likely stems from instrumental effects.

most improvements with a new replacement Software Defined Radio (SDR) for data acquisition, an improved temperature monitoring system for calibrations, a new full stokes digital spectrograph, and a new data reduction pipeline. Additionally, a new balun and amplifier pair were characterized over temperature in the lab and the transducer gain models used for calibration were explicitly computed by microwave network theory. Following these upgrades, we were able to observe continuously for several weeks and found evidence of induced polarization that is stable in sidereal time and that follows the expected behavior of physical simulations (Figure 4). With the lessons learned by this experiment, we are developing a new purpose-built instrument for follow-up observations and expanding the current simulation model to include additional physical effects from the instrument, atmosphere, ionosphere, ground, and sky.

1.2.2 Spaced-based Mission Concept and Data Analysis Pipeline

Within the first half of the year, the Colorado group led by Burns, completed and submitted (May 2019) an Astrophysics SmallSat concept study for the Dark Ages Polarimeter PathfindER (DAPPER). This study included developments in all key aspects of DAPPER, including the mission, spacecraft, instrument, and data analysis pipeline. DAPPER is well-aligned with NASA's current strategic plans for scientific research from the lunar environment. Working towards this goal, we developed a Statement of Work for instrument maturation that was presented to NASA leadership. This statement details a two-year plan for maturing the data analysis pipeline, the spectrometer/polarimeter and dipole antennas, the signal processing and calibration, and the digital signal processor development and evaluation platform, as well as all the corresponding interdependencies between these work packages.

We also completed the main structure of our data analysis pipeline of global 21-cm observations by incorporating the ability to convert the spectral constraints obtained analytically in the first segment of the pipeline (as described in Paper I of the series; Tauscher et al., 2018, ApJ, 853 187) into constraints on a nonlinear signal model of choice as presented Paper II (arXiv:1912.02205) by NESS team members Rapetti, Tauscher, Mirocha, and Burns. This second segment of the pipeline properly marginalizes over the linear description of the foreground model at each step of the Markov Chain Monte Carlo (MCMC) exploration of the nonlinear signal model of interest, allowing a faster, more efficient calculation.

1.2.3 Low Frequency Lunar Arrays

Several of the most pressing questions in astrophysics can be addressed by a low-frequency radio array telescope on the lunar farside. The key science goals of such an array include probing the growth of structure and thermal history of the universe during the cosmological Dark Ages using the 21-cm line of hydrogen. NESS's key astrophysics project aims to develop both technology and the motivating science for such an instrument. Technology development has been advanced through both full array concept design and detailed antenna design.

Existing radio astronomy antenna designs optimized for Earth-based arrays need to be modified for use in

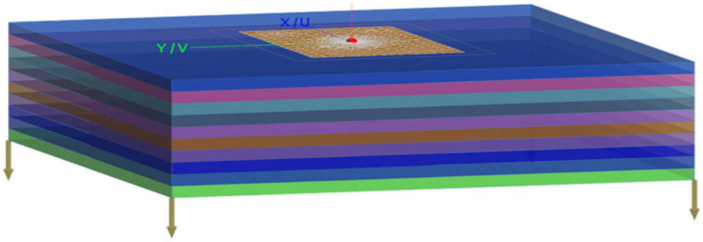


Figure 5: Electromagnetic model of a dipole antenna on the lunar regolith with subsurface layering used to investigate the sensitivity of the antenna to variations in the electrical properties of the regolith and underlying bedrock to assess the feasibility of a lunar global 21-cm measurement.

lunar radio telescopes to cover the desired frequency range and to account for the properties of lunar regolith. Deployment on the lunar surface is an additional functional constraint. The ASU team (Co-I Bowman, graduate student Mahesh) investigated antenna designs based on planar dipoles that could be deployed by rovers like those envisioned in the ROLSS concept. To optimize dipole antenna designs for a lunar telescope, the team used the well-understood beam patterns of the Experiment to Detect the Global EoR Signature (EDGES) low-band planar "blade" antenna as a reference. We assessed whether an EDGES-style experiment could be conducted on the lunar surface using a lunar radio array by modeling the antenna performance with and without an underlying ground plane. For the antennas without a ground plane (e.g. Figure 5), performance was found to be very sensitive to small changes in regolith properties. We investigated potential improvements to the antenna return loss of planar dipoles by 1) increasing the electrical path length for the currents on the surface and 2) by breaking the planarity requirement of the antenna, lifting the dipole panels at an angle from the regolith. Results are in preparation for publication.

1.2.4 Theoretical Predictions of the 21-cm Signal

One of the primary goals of low-frequency lunar telescopes is to observe the Cosmic Dawn, when the first stars and black holes illuminated the universe. The radiation fields from these sources can be observed indirectly through the redshifted 21-cm line of neutral hydrogen, for which the lunar environment provides an ideal observing platform. This is an extraordinarily weak signal, so a clear understanding of the signatures will help design the most effective lunar telescopes.

In 2018, Co-I Bowman et al. (2018) detected the first spin-flip signal from this era with the EDGES experiment. At UCLA, Co-I Furlanetto has led the effort to model the 21-cm signal from the Cosmic Dawn, using the EDGES detection as an example to illuminate the astrophysics we hope to learn. In Mirocha & Furlanetto (2019), we showed that the EDGES signal requires star formation to begin much earlier than expected from extrapolations from known galaxy populations: otherwise the radiation backgrounds would be insufficient to "turn on" the 21-cm signal. However, it has long been expected that the first generations of star formation differ from those in observed galaxy populations. In Mebane et al. (2020), we showed that these so-called "Population III" stars *can* explain the timing of the EDGES signal. Mebane's models provide a new framework to make predictions for lunar radio telescopes, and we are now extending them to predict finer-scale structure in the spin-flip background. Additionally, undergraduate student Fu and collaborator Mirocha continued to examine whether another potential type of source, globular clusters, could explain the timing of the EDGES signal.

Finally, Furlanetto's group is also developing improved models of "normal" galaxies at high redshifts. Identifying the exotic physics of Population III stars during the Cosmic Dawn will require a clear understanding of the normal galaxies into which their hosts grow. This new suite of models will allow us to extrapolate the observed galaxy populations with a physical basis, providing a tool for identifying the most robust signatures of exotic stars and helping to optimize lunar telescopes to detect those effects.

1.3 Heliophysics

As part of the Heliophysics and Space Physics key project of NESS, we are working on various projects that will help to design a lunar radio astronomy array. Our NESS science goals for heliophysics are solved primarily by the capability to produce images of solar radio bursts at frequencies below the imaging possible by ground-based arrays. Typically, they cannot image solar radio bursts below frequencies around 20 MHz, which corresponds to the terrestrial ionospheric "cutoff" frequency. The electron density in the ionosphere blocks electromagnetic waves below a certain frequency and distorts the waves at frequencies above the "cutoff" frequency. The frequency of 20 MHz corresponds to solar radio burst emissions only a couple of solar radii from the solar surface, so ground-based observatory imaging only covers a small fraction of the inner heliosphere.

At Michigan, Co-I Kasper and his graduate student turned postdoctoral fellow Hegedus have progressed on the Sun Radio Interferometer Experiment (SunRISE) mission concept. SunRISE is a Heliophysics Mission of Opportunity that is currently in an extended Phase-A period, pending full acceptance from NASA. SunRISE would consist of 6 CubeSats with radio receivers that together form an interferometer. SunRISE would circle the Earth in a GEO graveyard orbit and sample the low radio frequency range 0.1-20 MHZ and make rudimentary images below the ionospheric cutoff for the first time. Data is recombined on the ground, forming a synthetic aperture. SunRISE's primary science is to localize type II radio bursts within coronal mass ejections (CMEs) to identify the site of particle acceleration of solar energetic particles (SEPs), as well as to map the trajectories of energetic electron packets associated with type III bursts.

Deputy PI MacDowall leads a NASA lunar surface payload,

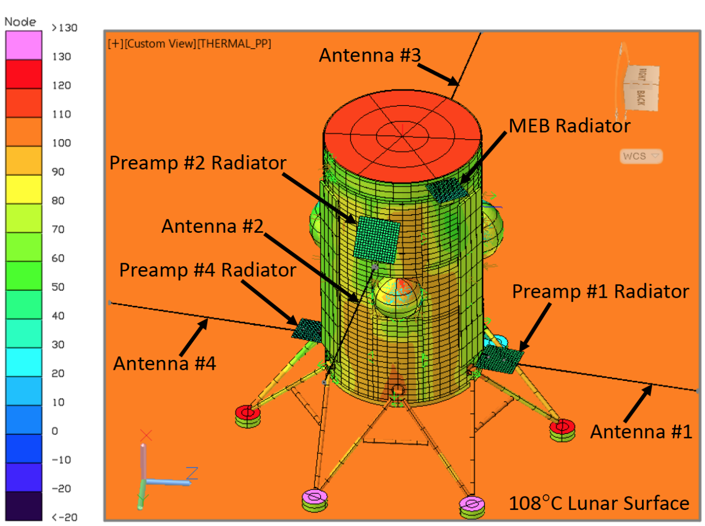


Figure 6: Diagram of the GSFC thermal analysis (degrees C) of the Intuitive Machines NOVA-C lander on the lunar surface and the radiator components of the ROLSES instrument (Major Electronic Box and four preamps for the four Stacer antennas). The radiators keep the electronics in their survival temperature range.

called ROLSES, which is a radio frequency spectrometer to be delivered to the lunar surface by Intuitive Machines (Figure 6). It will measure the scale height of the lunar surface photoelectron sheath, detect solar and planetary radio emissions from the lunar surface, document the current levels of radio frequency interference from Earth arriving at the lunar nearside, and possibly detect interplanetary dust impacts and reflection of radio waves from structures below the lunar surface.

1.4 Lunar Near-Side Earth Observing Radio Arrays

Applications of science analysis pipelines were also employed to explore an underdeveloped area of research: benefits from lunar near-side Earth observing radio arrays. In a project led by Hegedus at Michigan, with the guidance of Kasper and MacDowall, simulations of large-scale radio arrays provided estimates on scientific return for various sized arrays under various assumptions. This resulted in a paper recently published in Radio Science and presented at the NASA Exploration Science Forum. A radio array on the near side of the Moon would always be facing the Earth, and would be well suited for measuring its low frequency radio emissions, including weaker synchrotron emission. The specific geometry and location of the test array were determined using the most recent lunar maps made by the Lunar Reconnaissance Orbiter. This array would give us unprecedented day-to-day knowledge of the electron environment around our planet, providing reports of Earth's strong and weak radio emissions, giving both local and global information. Figure 7 shows a summary of the simulated synchrotron brightness, the array layout, and the reconstructed image output by the array under realistic noise conditions. The simulated synchrotron brightness comes from French colleagues at ONERA employing the modern iteration of the Salammbo code. The total brightness of the synchrotron emission observed from the Moon is estimated to be 1.4-2.0 Jy between 500-1000 kHz.

It was found that for normal amplifier noise-limited observations, a 16K element array in a logarithmic circular configuration over 10 km could yield a 3-σ detection of the synchrotron brightness in 2 hours. This figure may change depending on the level of quasi-thermal noise from free electrons on the lunar surface. Fortunately, this will be

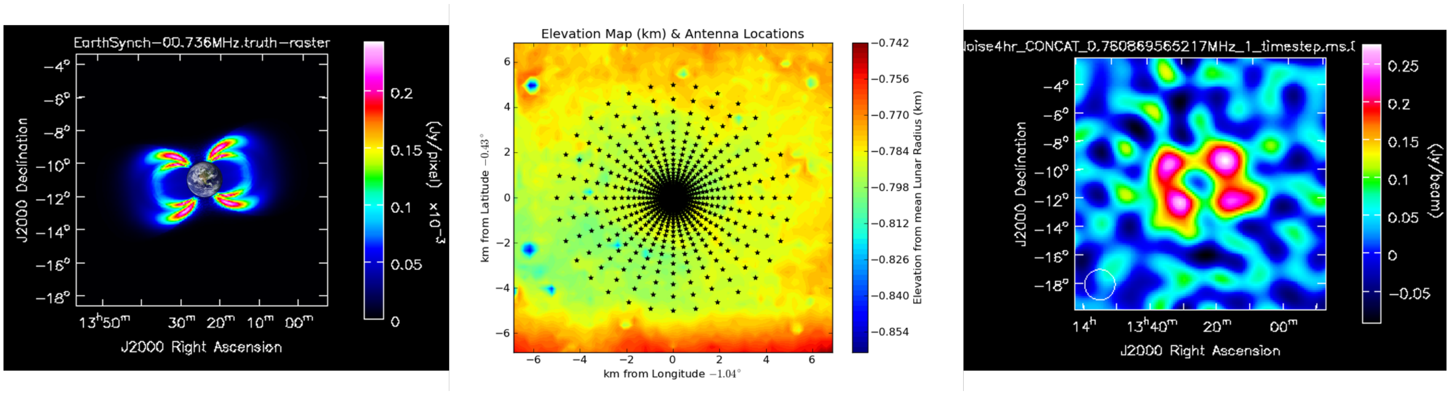


Figure 7: Left: Salammbo global electron simulation derived synchrotron brightness from Earth's radiation belts at lunar distances. Middle: Logarithmically spaced circular configuration of antennas across 10 km as a nominal array layout, centered on the flattest 10x10 km patch near the sub-Earth point. Right: Reconstruction of a 16K element array over 10 km with a 4-hour integration assuming limited amplifier noise.

investigated by ROLSES, described in the section above. On top of this weak, stable, global synchrotron signal lies a vast zoo of transient signals. An array sensitive enough to detect the weak synchrotron emission would have no problem characterizing transient signals many orders of magnitude more powerful. This ability of a large-scale lunar near-side radio array to provide a high degree of localization for transient emissions like Auroral Kilometric Radiation is scientifically compelling and could be started with a smaller pathfinder array.

2. Inter-team/International Collaborations

Hegedus, MacDowall, and Kasper joined up with ONERA, the French Aerospace Lab on a project. The work outlines a large-scale radio array on the lunar near-side that could detect and image Earth's synchrotron emission from energetic electrons for the first time (see also Section 2.4). ONERA supplied the simulated synchrotron brightness using a modern iteration of the Salammbo code. Salammbo is a global electron simulator that uses the Time History of Events and Macroscale Interactions during Substorms/Solid State Telescope (THEMIS-SST) data set of electron distributions up to several hundred keV as an outer boundary condition. The output is a global model of the trapped electrons in the radiation belts from 1 keV to 100 MeV, which can then be analyzed to compute the synchrotron brightness from a given vantage point. This was used as a test model for a simulated lunar radio array to detect and image the emission. The collaboration resulted in a publication in Radio Science cited above.

International team members Falcke and Klein-Wolt are leading the Netherlands-China Low-Frequency Explorer (NCLE), a low-frequency radio experiment for the Chinese Chang'e 4 mission that is in a Lissajous orbit around the Earth-Moon L2 point. NCLE is considered a pathfinder mission for a future low-frequency Moon-based radio interferometer which has the detection and tomography of the 21-cm Hydrogen line emission from the Dark Ages period as the principal science objective. Low-frequency radio astronomy below ~30 MHz can only be performed well from space due to the cut-off in the Earth's ionosphere, and the human-made noise that makes sensitive measurements from ground-based facilities impossible. At the Earth-Moon L2 point, NCLE is relatively far away from terrestrial interference, which, however, is still detectable. With the Earth always in sight, we can measure and quantify this emission for the first time in 50 years in unprecedented detail. This will allow NCLE not only to study radio and plasma physics of the Earth-Moon system, but also to explore mitigation and calibration techniques for exploring radio emission from true lunar farside locations made by future missions.

NESS also includes ongoing collaborations with the EDGES team to integrate lessons-learned on antenna performance to minimize spectral effects from foreground structure in the sky.

3. Public Engagement

The ASU team supported several public engagement events to reach both traditional and underserved audiences in the Phoenix metropolitan area. These included three annual events at ASU that served 5,000 visitors collectively. At these events, NESS graduate student N. Mahesh presented ongoing research and engaged the public with radio-astronomy themed word games and puzzles. Mahesh was also a panelist for the Young Change Makers at the Inspire India Youth conference; developed cosmology course materials for prison education; presented two seminars; and was a facilitator for Girls Who Code at the Heard School in Phoenix.

NESS celebrated International Observe the Moon Night on October 5th at Fiske Planetarium of CU Boulder. On July 12, 2019, P.I. Burns presented “Our Future in Space: The Moon & Beyond” for the Apollo 11 50th Anniversary Celebration at Fiske Planetarium, and the next day during the Apollopalooza celebration at the Wings Over the Rockies Air & Space Museum.

Burns led a talk-back session on May 1, 2019 after the audience watched the film “Apollo 11,” which is a cinematic space event film fifty years in the making, featuring never-before-seen large-format film footage of one of humanity’s greatest accomplishments: travelling to the surface of the Moon. Burns did 14 press interviews related to the Apollo 11 anniversary through August 2019.

NESS participated in ‘Astronomy Day’ on April 6, 2019 organized by Fiske Planetarium and Sommers-Bausch Observatory. The theme of the event was “THE MOON - Appreciating our Nearest Neighbor.” It was a full day of free family-friendly activities, telescope observing, light labs, scale Solar System tours, stomp rockets, comet labs, and planetarium shows focused on our Moon. NESS PI Burns delivered the keynote presentation for Astronomy Day titled “Our Future in Space: The Moon and Beyond” at Fiske Planetarium.

With supplemental outreach funding from SSERVI, NESS began a Public Engagement program centered around an immersive, full-dome planetarium video production featuring NASA plans for human and telerobotic exploration of the Moon using Orion, the Lunar Gateway, and Artemis infrastructure. The production highlights in-situ resource utilization, science research efforts, and long-duration operations in cis-lunar space. The project draws upon subject matter expertise from researchers affiliated with NESS along with two other SSERVI teams. In addition, Lockheed Martin, a primary contractor involved in development of Orion and the Gateway, is providing both in-kind expertise and financial support for the production. The 25-minute video will engage students and public audiences in a three-part story that a) starts with a vision for building infrastructure for lunar exploration and in-situ resource utilization, b) progresses to scientific research investigations enabled by lunar exploration, and c) extends lessons learned from lunar exploration as a guide for human exploration of Mars.

4. Student/Early Career Participation

Undergraduate Students

1. Kristy Fu (until Spring 2019), University of California Los Angeles, theoretical predictions of the spin-flip background.
2. Alex Sandoval (until graduation in May 2019), University of Colorado Boulder, Surface telerobotics - Instrumentation.
3. Arun Kumar, University of Colorado Boulder, Surface telerobotics - Instrumentation.
4. Mason Bell (beginning May 2019), University of Colorado Boulder, Surface telerobotics - Instrumentation.

Masters Student

1. Benjamin Mellinkoff (graduated May 2019 with an M.S.), University of Colorado Boulder, Surface telerobotics - Instrumentation.

Graduate Students

1. Richard Mebane, University of California Los Angeles, theoretical predictions of the spin-flip background.
2. Keith Tauscher, University of Colorado Boulder, Physics/Astrophysics/Cosmology, Dark Ages/Cosmic Dawn – Theory/Data.
3. Neil Bassett, University of Colorado Boulder, Astrophysics/Cosmology, Dark Ages/Cosmic Dawn – Theory/Data.

4. Joshua Hibbard (beginning August 2019), University of Colorado Boulder, Astrophysics/Cosmology, Dark Ages/Cosmic Dawn – Theory/Data.
5. Adam Trapp, University of California Los Angeles, Astrophysics, Cosmic Dawn-Theory.
6. David Bordenave, University of Virginia, Astrophysics/Cosmology, Dark Ages/Cosmic Dawn - Experiment.
7. Nivedita Mahesh, Arizona State University, Astrophysics, Cosmic Dawn - Experiment.
8. Michael Walker, University of Colorado Boulder, Surface telerobotics - Virtual Reality Telerobotics simulations.

Postdoctoral Fellows

1. Jordan Mirocha, McGill University, Astrophysics/Cosmology, Dark Ages/Cosmic Dawn - Theory.
2. Alex Hegedus (first nine months as a graduate student, then Postdoctoral Fellow), University of Michigan, Astrophysics, Heliophysics.
3. Bang Nhan, University of Virginia, Astrophysics, Cosmic Dawn - Experiment.
4. Midhun Menon, University of Colorado Boulder, Surface Telerobotics - Virtual Reality Telerobotics Simulations.
5. Marin Anderson, California Institute of Technology, Astrophysics, Cosmic Dawn – Theory/Data.

New Faculty or Staff Members

1. David Rapetti (about first eight months as a Senior NPP Fellow, then Visiting Scientist at NASA ARC), University of Colorado Boulder/NASA Ames Research Center/Universities Space Research Association, Astrophysics/Cosmology, Dark Ages/Cosmic Dawn – Theory/Data.
2. Stuart Bale (new to NESS), Professor of Physics, University of Berkeley, Plasma Astrophysics & Low Frequency Radio Astronomy - Experiment.

5. Mission Involvement

DAPPER: PI Burns– a NASA-funded concept study of DAPPER led to the design of a science instrument consisting of dual orthogonal dipole antennas and a tone-injection spectrometer/polarimeter based on high TRL components from the Parker Solar Probe/FIELDS, THEMIS, and the Van Allen Probes. DAPPER will probe the Dark Ages for the early universe for the first time with a smallsat in orbit of the Moon.

FARSIDE: PI Burns-- the Farside Array for Radio Science Investigations of the Dark ages and Exoplanets is a Probe-class concept to place a low radio frequency interferometric array on the farside of the Moon. A NASA-funded design study, focused on the instrument, a deployment rover, the lander and base station, delivered an architecture broadly consistent with the requirements for a Probe mission.

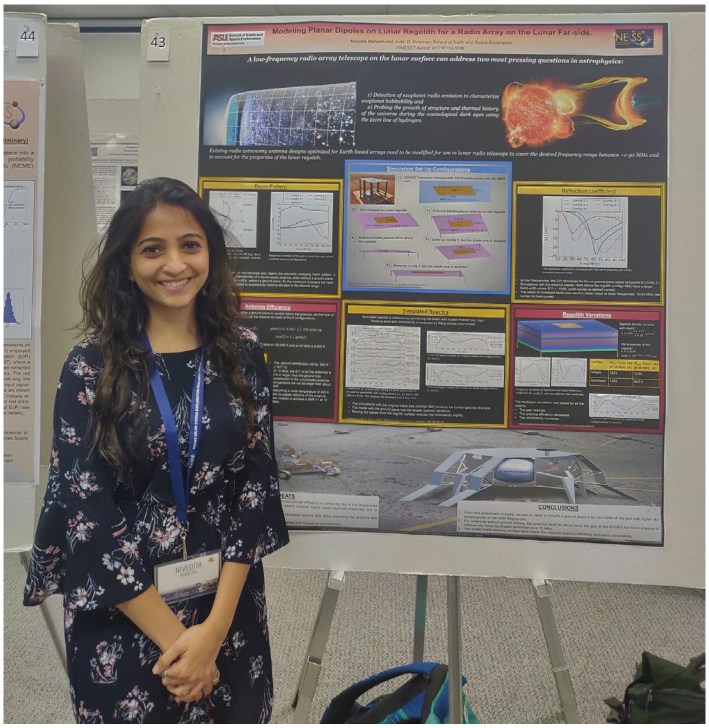
SunRISE: Kasper and Hegedus have progressed on the Sun Radio Interferometer Experiment (SunRISE) mission concept. SunRISE is a Heliophysics Mission of Opportunity that is currently in an extended Phase-A period, pending full acceptance from NASA. SunRISE would consist of 6 CubeSats with radio receivers that together form an interferometer.

ROLSES: ROLSES is a selected CLPS payload. Led by MacDowall, the goals of the Radio wave Observations at the Lunar Surface of the photoElectron Sheath (ROLSES) include determination of the photoelectron sheath density above the lunar surface and demonstration of the detection of solar, planetary, and other radio emission from the lunar surface.

LuSEE: The Lunar Surface Electromagnetics Experiment (LuSEE), led by Bale, will study the magnetic and electric fields on the Moon's surface and how they interact with fine dust particles. LuSEE is a selected CLPS payload.

6. Awards

Nivedita Mahesh (ASU Graduate Student) was awarded a NASA FINESST (Future Investigators in NASA Earth and Space Science and Technology) fellowship based on her proposal to build on her NESS-supported research. She also earned the NASA Exploration Science Forum (NESF) Best Poster award in July (see Figure 8).



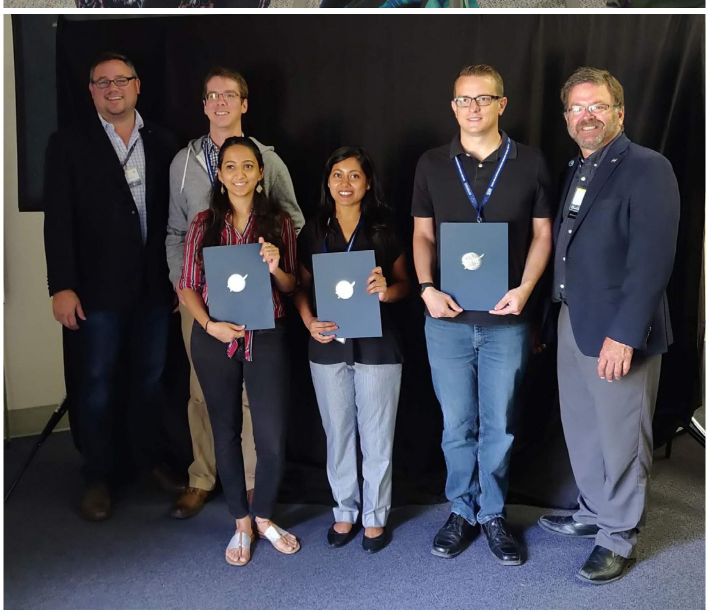


Figure 8: (Top) Nivedita Mahesh next to her poster awarded NASA Exploration Science Forum (NESF) Best Poster. (Bottom) Nivedita and others receiving awards at NESF.

Radiation Effects on Volatiles and Exploration of Asteroids & Lunar Surfaces (REVEALS)

Thomas Orlando

Georgia Institute of Technology in Atlanta, GA

CAN 2 TEAM

1. Reveals Team Report

1.1 Solar Wind and Thermal Activated Water Formation on the Moon and Mercury

In general, the sources of lunar water include primordial water, comet and meteorite delivery, and a pathway related to the solar wind. The latter was modelled and experimentally verified by the REVEALS team. Specifically, a small amount of molecular water is formed thermally on the Moon from recombinative desorption (RD) of -OH defects made by implantation of solar wind protons. Second order RD activation energies of Apollo highland and mare samples were measured using temperature program desorption (TPD). Water formation, adsorption and transport though the porous medium and activated sub-surface diffusion/ penetration were found to reproduce the experimental TPD signals. Furthermore, at typical temperatures prevailing on Mercury's dayside surface, H_2O is easily produced from RD. Similar reactions will also occur due to micrometeorite impact events on both the day and nightside. As shown in Figure 1A and B, the proton flux and temperature profiles lead to region-specific water formation (Fig. 1C) via RD (Fig. 1D). Once produced, H_2O is released into the exosphere and then transported and processed via Jeans escape, photodissociation, dissociative adsorption, or condensation. Water reaching cold traps will then be bound over geological periods.

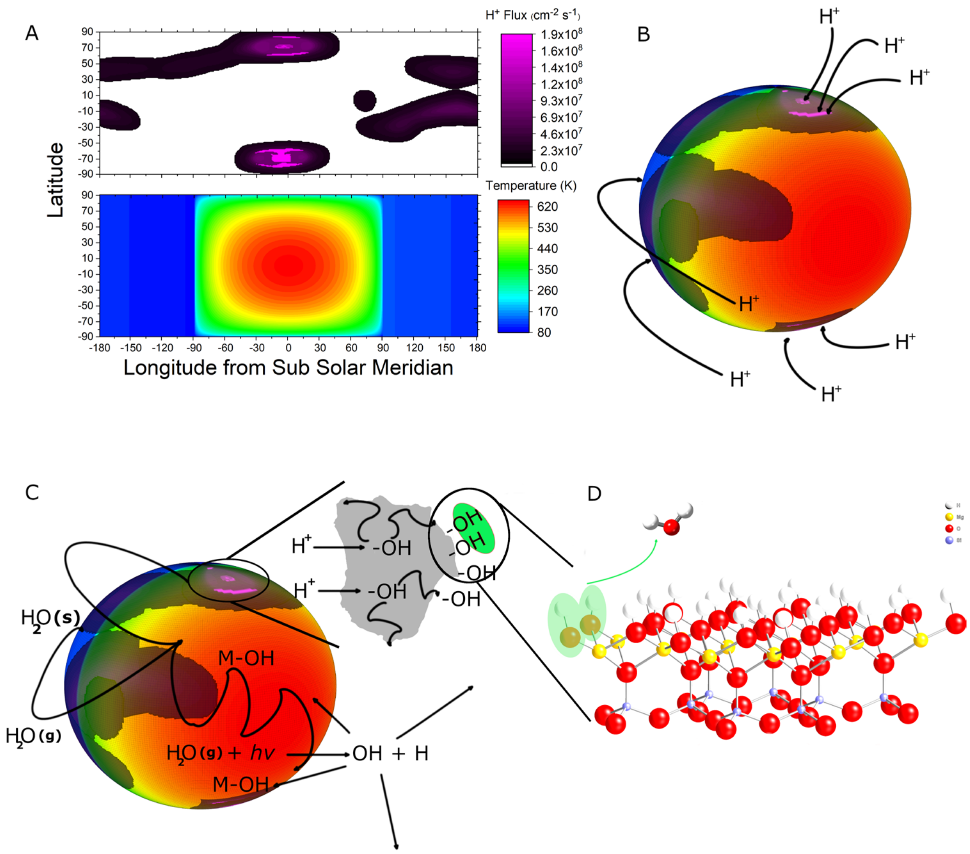


Figure 1: A) Average temperature (lower frame) and precipitating proton flux (upper frame) B) Solar wind protons impact of Mercury soil results in formation of hydroxyl (-OH) groups. C) OH groups will diffuse where they can react and form gas phase H2O thermally or photon stimulated RD. H2O is then ejected into the exosphere where it can undergo photodissociation resulting in radical fragments that, if recycled, can react and replenish surficial -OH groups. Of those molecules that survive photodissociation, water may dissociatively adsorb or condense if the local temperature is below the sublimation point. D) Expanded atomic view of the RD process leading to formation of H2O. Ref. Jones, et. al, The Astrophysical Journal Letters, 891:L43 (8pp), 2020.

This simple water cycle will produce a highly chemically reduced surface and can deliver significant amounts of H_2O to the permanently shadowed regions of Mercury over geological time periods. The overall process is an important but hitherto unnoticed source term that will contribute to the accumulation of water in the cold traps and polar regions of Mercury.

This water cycle also happens on all airless bodies subjected to the solar wind and temperature excursions above 350K. In the case of the Moon and asteroids, the main source of surficial and water in the permanently shadowed regions would be from delivery events and RD induced by meteoroid impacts, not the simple dayside and diurnal temperature cycling.

1.2 Space Weathering and Volatile Formation via Simulated Meteoroid Impact Events

Space weathering of Solar System bodies in the inner and outer Solar System involves medium velocity (>3 km/sec) meteoroid impact events. To examine this, REVEALS has developed a table-top meteoroid bombardment system based on the use of a laser induced micro-particle accelerator (LIMA) or laser induced particle impact testing (LIPIT) stage. This system is shown in Figure 2 and uses a high energy pulsed 1064 nm Nd:YAG laser to irradiate the backside of a thin nanostructured foil target or a thin metal foil/film covered with an elastic polymer. Mineral and lunar-dust grains that are deposited on the front face of the launching target are accelerated off the substrate toward a collision target of interest, e.g. a lunar mare or highland slab or polymer material to be developed for spacesuit applications. The velocity distributions of the grain projectiles are being measured either directly using a fast-frame camera or optically using a stroboscopic approach. The latter uses a second 532 nm laser that passes through an optical delay. The chemical products formed and removed during impact are measured with laser detection, and those remaining with nanoscale scanning spectroscopies and various surface analytical tools.

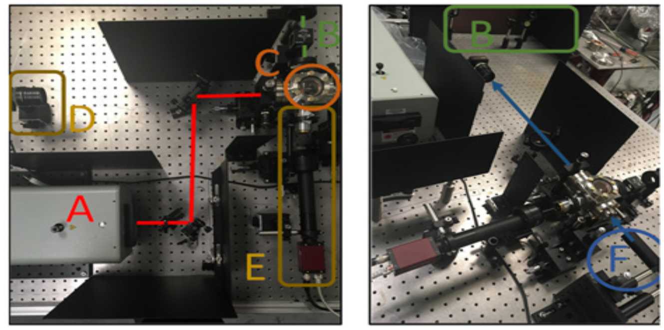


Figure 2: Left side: photo of the LIMA set-up showing the YAG laser (1064 nm) used to launch particles (A), part of the beam path for the second laser (532 nm) used for velocity measurements (B), main chamber with the launching substrate inside (C), the ancillary camera (D) used to image the substrate through a dichroic mirror, and the detection camera to photograph the moving particles (E).

The ability to study impact events involving mineral grains and lunar material followed by analysis of the departing and remaining chemical products is a critical aspect of understanding one of the dominant pathways of space weathering and volatile production.

1.3 Transport and Chemical Equilibrium Modelling for ISRU Applications

Lunar *in-situ* resource utilization (ISRU) is of great interest to the lunar exploration community since it is necessary for the sustained presence of humans on the Moon. A promising technology to harvest H_2O is by thermal extraction using focused solar radiation. An experimental apparatus was fabricated and used to study gas transport in regolith under lunar-like conditions to aid in designing thermal extraction technologies. The study evaluated Ar and N_2 gas flow within JSC1A, a surrogate lunar medium. It provided a framework for moving towards more complex volatiles such as H_2O and showed that the advection diffusion model, typically applied to bulk volatile transport for ISRU, needs to be verified even for the simplified cases (Ar and N_2) studied. In addition to water, lunar regolith can also be a potential source of O_2 and reduced metals. Chemical equilibrium modeling was performed to forecast chemical compositions as a function of temperature at pressures relevant to the Moon. Gibb's Free Energy minimization ($\Delta G = 0$) was used to predict equilibrium compositions for isobaric processes. A defined temperature range is predicted for favorable O_2(g) evolution with a dramatic increase in O_2(g) occurring at ~800 °C and peaking at ~ 950 °C. In addition to useful volatile formation and release, molecules know to be toxic, such as OCS, HCN, etc., were predicted to form during solar heating based on the volatiles reported for the LCROSS impact event.

1.4 Mineral Surface Chemistry: TPD Characterization of Al-OD-Si Sites at the Interface of Bilayer Al0.42Si0.58O2/ Ru(0001) Thin-films

Temperature programmed desorption (TPD) has been used by REVEALS team members to isolate and investigate water interactions unique to bilayer $Al_{0.42}Si_{0.58}O_2$/Ru(0001) via comparison with identical water TPD experiments on a polymorphically equivalent bilayer SiO_2/Ru(0001) sample. Relative to SiO_2, the aluminosilicate shows evidence of additional desorption processes leading to TPD peaks near 400, 500, and 600 K, with the highest temperature feature exhibiting excellent agreement to previous results documenting infrared monitored loss of Al-OD-Si sites from nominally identical samples. The second order desorption energy estimated from this peak is ~1.6 eV, which is considerably lower than that reported for conventional zeolites, but potentially on par with desorption features reported from other minerals within the feldspar family. Quantification of the peak intensity suggests a ~5% likelihood for formation during water condensation and subsequent desorption. The lower temperature features have been assigned to desorption of molecular water bound at the excess hydroxyl sites. Each hydroxyl appears to bind 2 additional water molecules, which then desorb in a stepwise sequential process. The same low temperature TPD features are also apparent after creating silanol groups on (Al-free) SiO_2/Ru(0001) via electron bombardment of supported ice layers, indicating similar water-OH-film interactions independent of specific OH site type.

1.5 Characterization of Multilayer Epitaxial Graphene and Prototyping a Graphene-based Radiation Sensor

The low-energy electronic structure of multilayer graphene has been examined by the REVEALS team. The electrons in graphene exhibit a four-fold degeneracy, accounting for the spin and K/K′ valley symmetry (Figure 3), which may have profound implications in future materials and device applications. To fully understand the spin and valley degenerated ground state of graphene, a high magnetic field was used to lift the degeneracies and circular-polarized light was used to selectively probe the optical transitions between the Zeeman and valley split energy levels. Our measurements reveal effective g-factors of gVS* = 6.7 and gZS* = 4.8 for the valley and Zeeman splittings, respectively.

A graphene-based radiation detector was also fabricated, and testing with x-ray irradiation has begun. The graphene was vapor-deposited onto a Cu foil, isolated via a ferric nitrate etchant and placed atop a polished, marked Si substrate. This graphene was spin-coated with a negative resist and subjected to electron beam lithography to etch a hall-bar pattern of graphene (Figure

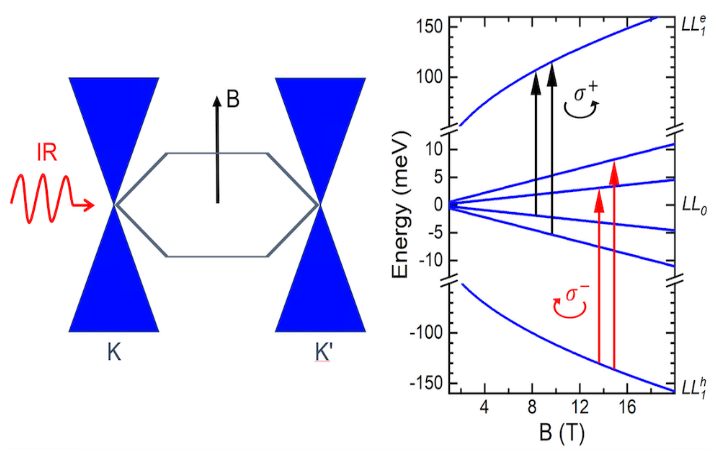


Figure 3: Broken-symmetry states in multilayer epitaxial graphene revealed by high-magnetic-field circular-polarization resolved infrared spectroscopy.

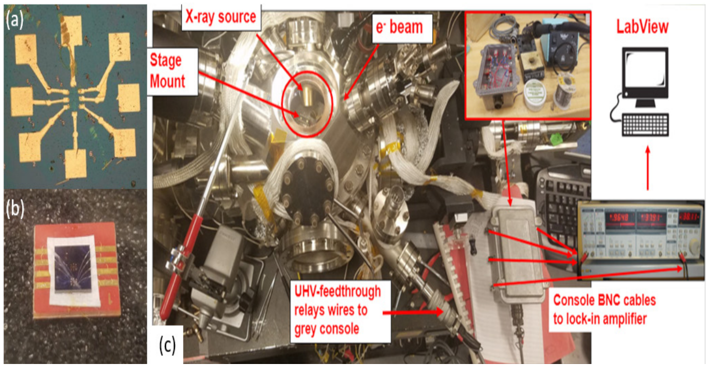


Figure 4: (a) Electron beam lithography and gold-deposition were used to create graphene hall-bars surrounded by 8 gold contacts. (b) These contacts were wire-bonded to an 8-leg stage, which can mate directly to the stage mount of an XPS chamber for x-ray studies.

4a). The remaining graphene was removed via O2 plasma treatment. Further electron beam lithography was used to create eight contacts, each corresponding to hall-bar terminals (Figure 4b). After gold-deposition and subsequent wire-bonding to an 8-leg stage, the device is mounted in a custom ultrahigh vacuum chamber (Figure 4c) for x-ray irradiation. Device concepts for micropower radiation dosimeters based on quasi-two-dimensional materials such as graphene and hexagonal boron nitride have been disclosed in provisional patents. These new meta-material configurations are designed for easy manufacturability, adaptability to different detection geometries, mechanical flexibility, enhanced detection sensitivity, polymer encapsulation, and low power.

> Two-dimensional meta-materials may be used to produce ideal real-time radiation detectors for active dosimeters that can be integrated into spacesuits and hardware for extra-vehicular and surface exploration.

1.6 Real-Time Radiation Dosimetry Reporting to an EVA Astronaut

Astronauts conducting surface Extravehicular Activities (EVA) will be in minimally shielded regions and will therefore be subjected to ionizing radiation. This is known


Figure 5: UC Davis' Janine Moses testing REVEALS Helmet HUD concept on EMU helmet.

to have potentially deleterious health effects which include cancer and cardiovascular issues. To directly address this critical safety issue, REVEALS has also been working on integrating very sensitive radiation detectors and display technologies with current and anticipated space suit designs (Figure 5). Specifically, prototype radiation-reporting displays that minimize operational risks to EVA astronauts have been developed and tested. Thin, flexible, organic light emitting diodes (OLED) monochrome displays were integrated into military pilot helmets. The displays are driven by microprocessor circuits and software developed in the UC Davis HRVIP Lab. These were initially tested with simple UV photodiodes at UC Davis. The current goal is to test the display hardware and driver software (including voice-commanded display options) in suited underwater Neutral Buoyancy Laboratory (NBL) runs by early summer, 2020. For these NASA JSC NBL tests, the current and accumulated metabolic rate statistics will be monitored which is an essential dynamic metric to the suit-wearer. Our eventual objective is to display radiation dose rate statistics to an EVA astronaut using the 2D meta-material flexible detectors being developed by REVEALS.

1.7 Novel Polymers for Spacesuit and EVA Applications

Protoype models of form fitting 3D-printed polymer-based materials for human spacesuits (head and torso),

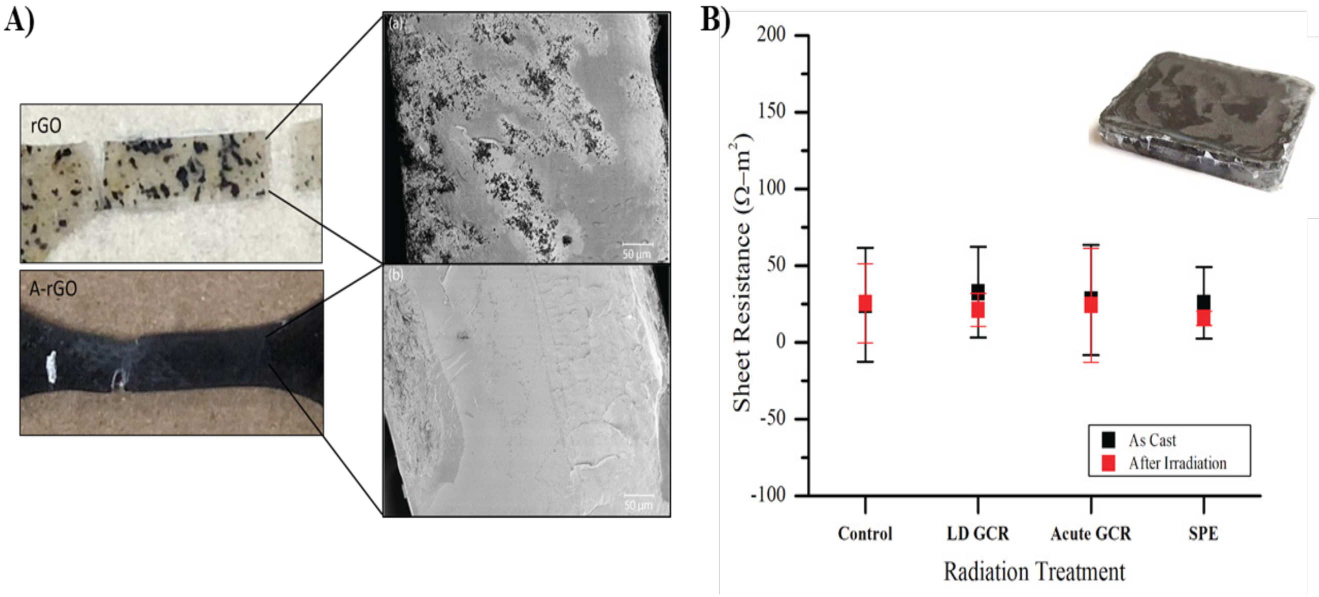


Figure 6: A) Cross-sectional scanning electron micrographs of HDPE composites reveal decreased aggregation when using functionalized reduced graphene oxide as a reinforcement material. B) Sheet resistance of HDPE films laminated with functionalized rGO before and after simulated radiation.

and Equipment/Life support systems (ECLSS) to protect other equipment for crew surface operations are being developed. Primary efforts to develop the polymers necessary for these applications focused on developing a synthetic protocol to incorporate reduced graphite oxide (rGO) into a high-density polyethylene (HDPE) matrix. Due to the enhanced dispersion throughout the bulk of the composite (Figure 6A), the mechanical properties remain largely unaffected by the functionalized rGO. However, the sheet resistance was high. In order to improve electrical conductivity, a lamination processing strategy to incorporate functionalized rGO at the composite surface was developed. Proto-type composite architectures included blended, laminated, and fiber-reinforced form factors.

1.7.1. Electrical Properties of Irradiated and Non-irradiated Polymers for Spacesuit Applications

The tolerance of the functionalized rGO laminates to simulated galactic cosmic ray (GCR) and solar particle event (SPE) irradiation was initially examined at the NASA Space Radiation Laboratory at Brookhaven National Laboratory. No significant changes in sheet resistance were observed for acute and low-dose rates as shown in Figure 6B. Polymer samples (as-machined HDPE, conductive HDPE with functionalized rGO, and conductive HDPE with a graphite surface coating) were also irradiated with 64 MeV protons at the UC Davis Crocker Nuclear Laboratory. Additionally, as-machined HDPE samples were tested at Notre Dame University. The as-machined untreated (non-conductive) HDPE samples are very resistant to radiation and have unchanged properties under the given dose. The non-destructive Electrical Resistance Tomography technique was also used at UC-Davis to examine the irradiated conductive HDPE samples. The samples were exposed to protons with a dose of 50 Gy in a localized area with the resistance map shown Figure 7. Though this is a high dose rate, Electrical Resistance Tomography may prove to be a sensitive method of detecting localized radiation damage.

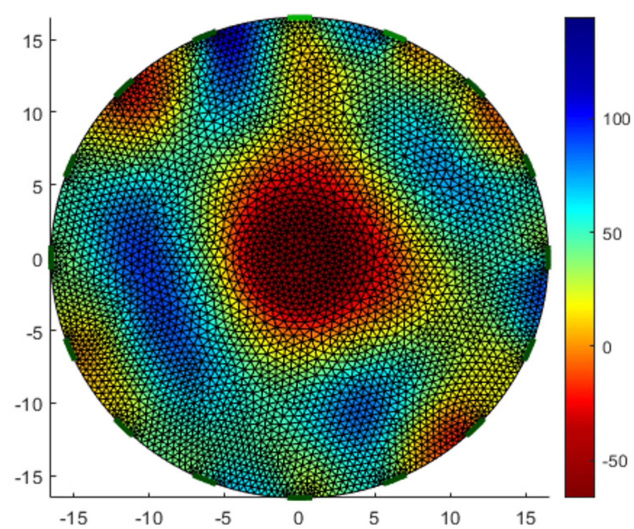


Figure 7: Electrical resistance tomography map shows localized radiation damage of irradiated HDPE sample

1.7.2. Parametric Study of the Tensile Properties of High-density Polyethylene (HDPE)

The strength and tensile properties of larger scale samples of HDPE in various geometries across several scales encompassed by ASTM D638, typical of polymers, and by D3039, typical of reinforced polymers, were tested at UC-Davis with strain gauges and an extensometer. The HDPE samples were water-jet machined to the appropriate shapes. The results, with the support of Monte Carlo simulations and finite element analysis, identified D638 Types II and IV to be statistically equivalent to D3039. This work can be applied to the effective design of space suits, 3D-printed space infrastructure, and 3D-printed designs in general.

Novel composites can be used to produce radiation resistant, mechanically strong and electrically conductive flexible polymers for spacesuit and multiple EVA applications.

2. Inter-team/International Collaborations

CLASS Collaborations: Regolith Shielding and Volatile Transport

Collaborations with Dan Britt (UCF) continue on understanding the thermal production and release of water and other volatiles from asteroid simulants developed in the EXOLITH lab. These simulants are now being used by REVEALS team (Schieber, Clendenen and Loutzenhiser) in measurements of diffusion and transport coefficients of volatiles such as Ar and water in regolith. D. Britt (CLASS-PI) is also a member of the REVEALS advisory board.

Polymer irradiation experiments at Brookhaven National Laboratory will continue with collaborations with Beltran (CLASS/REVEALS), Zhang (Kennedy Space Center), Siebers (REVEALS) and LaSaponara (REVEALS). The efforts will focus on understanding the chemical stability of the modified HDPE polymers as effective shielding materials.

VORTICES Collaborations: Temperature Programmed Desorption and Formation of Water from Regolith

Collaborations with Hibbitts (VORTICES) and Dyar (VORTICES) on understanding the kinetics and mechanisms of temperature-induced release and formation of molecular water from lunar regolith and surface material continue. They have demonstrated the importance of the binding energy distributions and the very important role of solar wind induced hydroxylation and recombinative desorption in forming water at temperatures above 350K. Note Andy Rivkin (VORTICES-PI) is a member of the REVEALS advisory board.

DREAM2 and IMPACT Collaborations: Health Effects of Charged Dust Grains

Dr. Micah Schiable, a NASA Program Postdoctoral Fellow, is working with IMPACT and DREAM2 in developing an apparatus and testing protocol to examine the effects of grain charging on health. Specifically, the program mainly examines the interaction of charged grains with surrogate lung membrane surfactants. The program is generally geared towards understanding and controlling grain charging effects on chemistry. It will continue with future support for Schiable involving LEADR. Note William Farrell (DREAM2-PI and LEADER Co-I) is also a member of the REVEALS advisory board.

International Collaborations:

Germany/ESA

Dr. Katherina Fiege was supported by ESA as a Visiting Scientist to continue the SSERVI/REVEALS collaboration with Altobelli (ESA), Srama and Trieloff (University of Heidelberg) on understanding the optical and chemical signatures of interstellar dust collected by the Cosmic Dust Analyzer. She also completed studies of the IR optical signatures of mixed ice samples containing dust grains for future space weathering studies.

Sapienza University- Italy

LaSaponara (REVEALS) is continuing her long-term collaboration with Laurenzi and Santonicola (Sapienza University-Italy) on characterization of UV-C radiation sensors based on graphene/DNA dispersed polymers. This effort is related to the 2D topological material approach that deals with measuring ionizing radiation.

3. Public Engagement

Education and public outreach activities take many forms across the REVEALS team and are integral to our core values. Educational opportunities seek to engage students at many different stages of their educational career and provide them training and inspiration in the STEM fields, while Public Engagement and Outreach activities seek to expose the greatest number of people to the awe, excitement, and inspiration that comes through space exploration and technology development. Beyond lectures, tours, mentoring, and remote Q&A sessions, there is also the Museum Installation Project which will produce a long-lived site for continuous public education.

3.1 Summer Camps and Robotics Teams

Many of the REVEALS team advise and mentor students in a variety of summer programs and robotics activities. Below are three of those programs, with Freedom Middle School's Research & Robotics Camp and the Georgia Tech Space Structures camp being designed and led by REVEALS team members with a plan to merge and grow sustainably over the next few years.

3.1.1 GroveBots First Lego Competition (Science Advisor: Dr. Esther Beltran, UCF)

The Grovebots, a team from Oak Grove Elementary school, participated in their First Lego League Robotics "Into Orbit" project. They advanced to the State Championships held on the Georgia Tech Campus 2/2/2019, and received the 1st prize and got the "Innovative Solution" Project Award.

3.1.2 Freedom Middle School Research & Robotics Camp (Program Lead: Carla Kabwatha)

Membership in the FMS Research and Robotics Camp program was comprised of Freedom Middle School students and students from other Title 1 schools in the DeKalb County District. The instructional curriculum was directly aligned to research currently done by REVEALS with focus on research questions and robotic design and programing. Students participated in a robotics challenge judged by Dr. Orlando and Dr. Jones (GT). (See Figure 8)

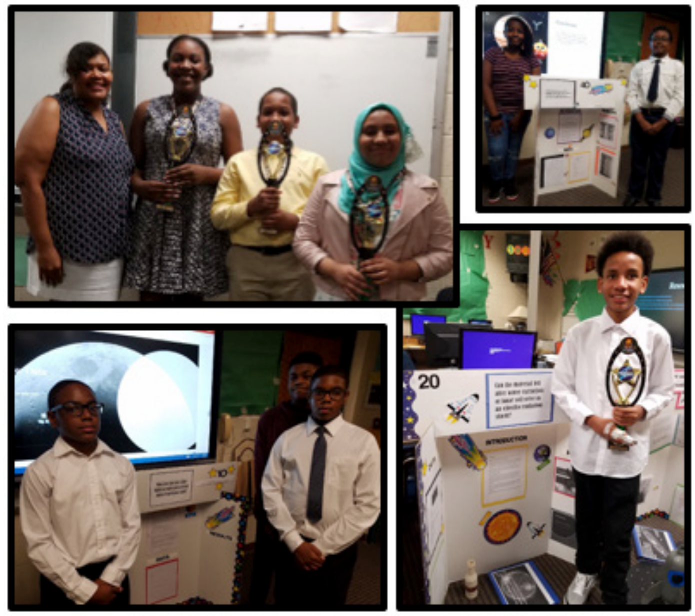


Figure 8. The Freebots team from Freedom Middle School in Stone Mountain, GA presented 'The Radiation Transformation: Decreasing Barriers to Long Term Space Travel,' winning the 1st Place Champion's Award in the First Lego League's (FLL) Regional Tournament, 1st Place Champions & Robot Game Award in FLL Super Regional Competition, and 3rd place at the Georgia Symposium on Space Innovations for their poster presentations!

3.1.3 TrussMe! Space Structures Summer Camp (Program Director: Dr. Julian Rimoli, GT)

This program was piloted as week-long pilot summer camp on design, manufacturing and testing of space-structures. Camp participants were high school students representing typically underrepresented minority groups in STEM. Students were exposed to the entire engineering design cycle during the camp.

3.2 Public Lectures and Engagement

There are too many lectures and engagement activities to list in such a short space, but a few of the high impact activities are listed below. REVEALS members from all participating universities gave public lectures at libraries, museums, colleges, and planetariums, served on the Astronaut Foundation Scholarship selection committee, and participated in a space themed 'Apollo 50th' homecoming football game (Drs. Kaden and Beltran - UCF).

3.2.1 Space Track at 2019 Dragon Con

Dr. Valeria La Saponara, Dr. Esther Beltran, Dr. Thom

Orlando, Dr. Micah Schiable, and Dr. Stephen Robinson served on multiple panels and gave lectures in the Science Track at Dragon Con. They discussed radiation mitigation research, the preparation of engineering students for the space industry, space gadgets, astrobiology, Sci-Fi, and human exploration.

3.2.2 Apollo 50th: Apollo Palooza

Dr. Carol Paty and graduate students from the University of Oregon partnered with the Eugene Science Center and the local Astronomy Club for a full day of activities from building moon bases, remote controlled rovers, compressed air paper rockets, astronaut activity centers.

3.2.3 Scouts of America Outreach Day: Tower of Death

Dr. Valeria La Saponara and her students hosted the "Tower of Death" outreach event for a local Scouts of America's troop and their chaperones. The demo shows (destructively) crashworthiness, materials behavior, and bike helmets' safety

3.2.4 Apollo 12 Anniversary Special Presentation

Dr. Thomas Orlando presented a well-attended public lecture: "Going to the Moon Soon" at the Fernbank Science Museum/Planetarium.

3.3 Museum Installation Project: Aerospace Museum of California (Sacramento)

Dr. Stephen Robinson has partnered with the Aerospace Museum of California to design and install a "Space for You" exhibit. This project is in ongoing development and rolling out over the next 2 years. This process in the last year included leveraging an undergraduate course taught by a renowned museum design expert Dr. Tim McNeil, to develop a modular and updateable exhibit revolving around spaceflight and human exploration. The culmination of the course was a full day exhibition with hands on demonstrations and a detailed information session at the Museum. A graduate student has been selected to lead the build and implementation of the exhibit over the next 2 years with REVEALS funding support, and agreements with the Museum and a local junior college have been solidified to secure funding to purchase materials and fabricate the exhibits under their guidance.

4. Student/Early Career Participation

Undergraduate Students

1. **Ashley Royce**, University of Central Florida Internship, Graduated from University of Florida, Medical Sciences Awarded NASA-Florida Space Consortium Grant, 2019-2020.

2. **Hannah Lyons**, University of Florida, major in microbiology, Internship at UCF-FSI summers (2017, 2018, 2019) with Dr. Beltran. Accepted to Medical School at University of Florida, start date May 2020.

3. **Nicholas, Hamilton**, Georgia Institute of Technology, School of Physics. Contributing to the effort dealing with 2D meta-material radiation detectors.

4. **Steven Licciardello**, Georgia Institute of Technology, School of Physics. Contributing to the effort dealing with 2D meta-material radiation detectors.

5. **Charles E. Foster**, Georgia Institute of Technology, School of Physics. Contributing to the effort dealing with 2D meta-material radiation detectors.

6. **Kaden Jeppesen**, University of California, Davis, Kaden Jeppesen graduated from UC Davis in June 2019 and was accepted to Stanford's graduate program in Mechanical Engineering. He is now on an internship at NASA Ames in lunar robotics, and **reports that the REVEALS project was his "launchpad."Janine Moses**, University of California, Davis, Janine Moses graduated from UC Davis in June 2019. **She helped established a partnership with the NASA JSC EVA office** to continue the development of a helmet-mounted display (or "Helmet HUD") for application to spacesuits in use for Astronaut training at the JSC Neutral Buoyancy Laboratory (NBL).

7. **Ruby Houchens**, University of California, Davis. Contributed to the development of a helmet-mounted display (or "Helmet HUD") for application to spacesuits.

8. **Joshua Pollock**, University of Central Florida, Department of Physics. Contributing to the study of single-crystal surrogate lunar mineral surface reactions.

9. **Jillian Gloria**, University of Central Florida, Department of Mechanical and Aerospace Engineering. Contributing to the study of single-crystal surrogate lunar mineral surface reactions.

Graduate Students

1. **Kaden Jeppesen**, graduated MS from UC-Davis, Aerospace Engineering-Mechanical Engineering. **Obtained internship in Robotics at NASA Ames Research Center**. Project with robotics group on the VIPER Lunar Rover. Specifically, designing/ building test fixtures for the rover's sensors, and performing experiments with those fixtures. Start date 1/13/2020.

2. **Garrett Schieber-** Georgia Tech, PhD Engineering - PhD Student, Georgia Institute of Technology, Solar Fuels and Technology Lab. Expected Graduation from PhD program at Georgia Tech May 2020. **He will transition to a postdoctoral fellow appointment at CLASS.**

Ashley Clendenen, Georgia Institute of Technology, expected MS, Mechanical Engineering in Aug. 2020 based on ISRU modeling work and will pursue a Ph.D. in Physics at Georgia Institute of Technology concentrating on impact studies.

3. **Elliot Frey,** Georgia Institute of Technology, expected MS in Materials Science and Engineering in May 2020 and will pursue a Ph.D. in Materials Science and Engineering. Thesis topics deal with developing novel meta-materials for real-time radiation detectors.

4. **Faris Almatouq**, Georgia Institute of Technology, pursuing Ph.D. in Physics. Thesis topic deals with developing novel meta-materials for real-time radiation detectors.

5. **Bijoya Dhar,** Univ. of Central Florida, Ph.D. in Physics, expected graduation in May, 2020 based on studies of single crystal mineral surface reactions of relevance to lunar science.

6. **Reilly Brennan,** Georgia Institute of Technology, expected MS in Chemistry in May 2020. Thesis topic is on the development and testing of laser-induced micro-particle accelerator for regolith impact studies.

7. **Ian Dowding,** Georgia Institute of Technology, pursuing Ph.D. in Materials Science and Engineering, May 2020. Thesis topic is on the development and testing of laser-induced micro-particle accelerator for polymer impact studies.

Postdoctoral Fellows

1. **M. Schiable**, NASA Postdoctoral Program Appointee, working on dust grain charging and health effects with REVEALS, IMPACT, DREAM2 and LEADER.

2. **K. Fiege**, ESA Visiting Scientist, working on interpreting data from the CDA and carrying out Space Weathering experiments on mixed ices thought to be in the polar regions.

New Faculty Members

1. **Misha Sofner**, Georgia Institute of Technology, School of Materials Science and Engineering. Her research concentrates on characterization and testing of polymers and polymer composites.

2. **Julian Rimoli**, Georgia Institute of Technology, School of Aerospace Engineering. His research concentrates on structural dynamics and landers. Rimoli is the Director of the TrussMe! Space Structures Summer Camp.

3. **Carla Kabwatha,** Freedom Middle School, Director of Freedom Middle School Research & Robotics Camp

5. Mission Involvement

1. Europa Clipper, C. Paty, PIMS Co-I

2. Europa Clipper, C. Paty, REASON, Co-I

3. Europa Clipper, C. Paty, Interior Working Group Co-Chair

4. JUICE, C. Paty, Science Co-I

Toolbox for Research and Exploration (TREX)

Amanda Hendrix
Planetary Science Institute in Tucson, AZ

CAN 2 TEAM

1. TREX Team Report

The year started off with several Co-Investigators being furloughed due to the government shutdown, but soon thereafter the TREX team was up and running again with the business of science and exploration. The TREX team coordinated its work this year by holding monthly all-TREX telecons and more frequent Theme group and splinter tag-ups. Many TREXers were in attendance at the LPSC meeting in March, where an excellent in-person team meeting was held; this was a great opportunity to share TREX progress with SSERVI management in attendance. We also held a smaller in-person team meeting in Tucson in August, in conjunction with the Planetary Science Institute retreat. TREX results were presented widely at the LPSC, the NASA Exploration Science Forum, DPS and other meetings throughout the year.

1.1 The TREX Fine-Particle Spectral Library

Tremendous progress was made in 2019 on the TREX spectral library of planetary-relevant fine-grained (<10 mm) minerals. All measurements have been made and the data are in the finishing stages of being prepared for ingestion into the Tetracorder expert system (to be used during field work), and for archiving. Measurement of these ~28 terrestrial minerals was the first phase of the TREX spectral library; the second and third phases, measurement of meteorites and lunar samples, are now in their beginning stages. Looking ahead to 2020: The TREX meteorite samples request has been approved by the Meteorite Working Group and we expect the samples to be delivered in spring 2020.

1.1.1 Boulder Spectroscopy Workshop (February 2019)

The TREX spectroscopists held a very successful in-person meeting at LASP/CU in Boulder, CO Feb. 20 and 21. We shared and discussed data from each of the TREX laboratories (at CU/LASP, PSI, DLR and Univ. Winnipeg) to look at comparisons and what laboratory instrument fixes and calibration improvements need to be made. One outcome of the meeting was the decision to produce a new UV standard (platinum); Co-I Greg Holsclaw took the action to explore pricing and production of standards (see Sec 1.1.3).

Members of the TREX team at a meeting in Tucson (Aug. 2019)

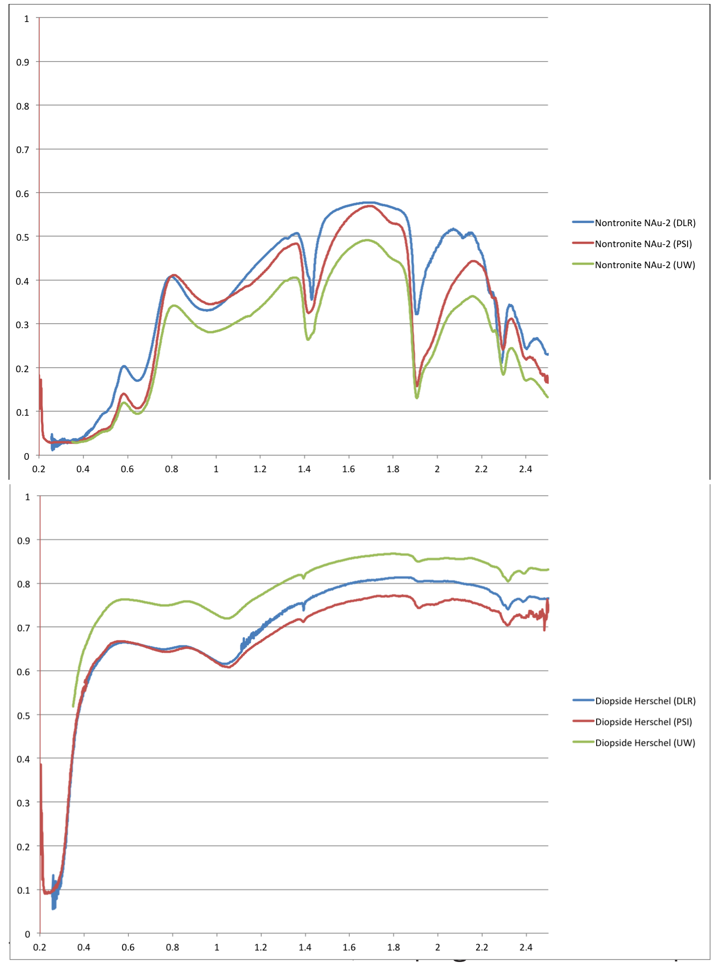
During the LASP workshop at CU, the team toured the new TREX UV lab (McPherson vacuum UV-VIS refl. System) recently assembled by TREX Co-I's Greg Holsclaw and Mikki Osterloo.

> The first phase of the TREX spectral library is now complete, with a set of 28 UV-MIR fine-grained (←10 mm) terrestrial mineral samples measured in reflectance under environmental conditions (pressure, temperature). This library will be critical for helping NASA scientists to interpret spacecraft data of airless bodies.

1.1.2 Reflectance Spectra of Fine-grained Minerals

The foundation of TREX work is the production of the TREX spectral library, which focuses on fine-grained (<10 mm) planetary materials measured over ultraviolet, visible/near-infrared, and mid-infrared (UV-VNIR-MIR) under environmental conditions that mimic the surfaces of airless targets (in vacuum, when possible, and at various temperatures). This library will be invaluable in interpreting spacecraft data (e.g. for Moon and small bodies tasks outlined below) and will be made available to the larger community as well. Furthermore, the spectral library will be ingested into software used in autonomous sample selection during TREX fieldwork (Sec. 1.3). The lab measurements will include a range of pure terrestrial minerals, lunar samples and meteorites. A goal of performing measurements in a suite of labs is to harness both unique and overlapping capabilities to derive a robust set of cross-calibrated laboratory spectra. The first phase of the spectral library production has been completed in 2019: we now have a complete set of 28 terrestrial minerals. Some sample spectra are shown below.

Another new development in the spectral library was the establishment of the TREX UV lab at CU/LASP. The new TREX UV lab at LASP (picture below at left) allows us to measure the ultraviolet-visible reflectance of geologic samples in vacuum. Compositionally diagnostic spectral

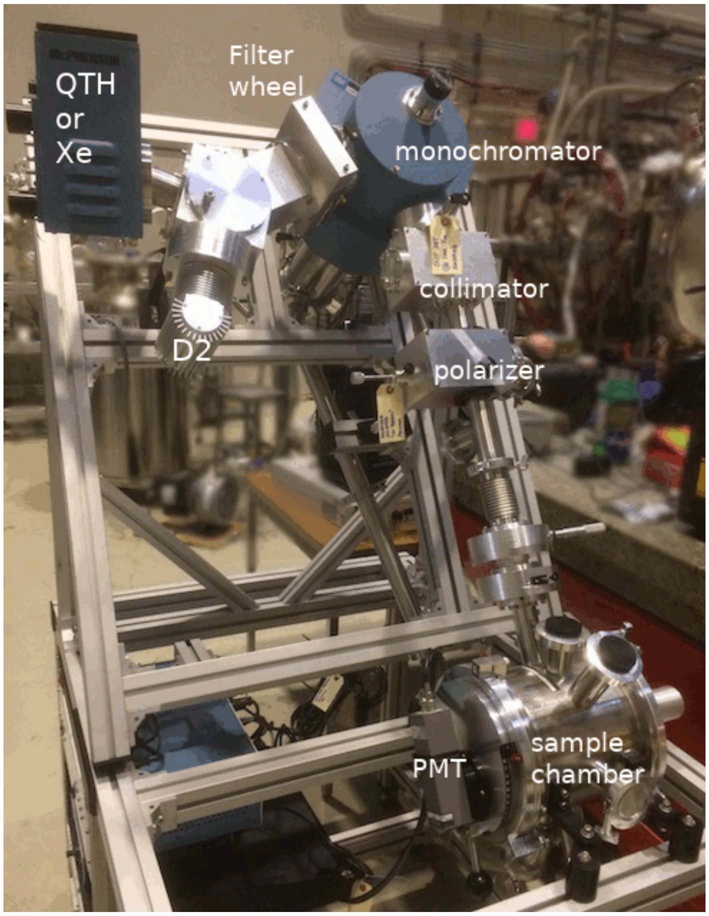


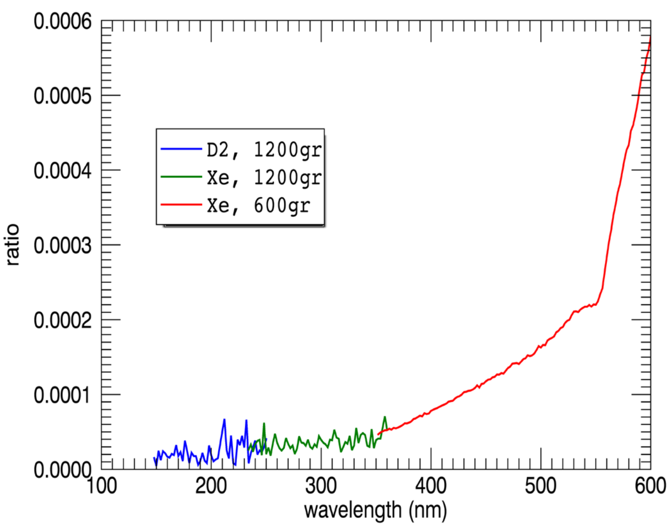
Shown here are two example spectra (of 28 terrestrial samples) from three TREX labs: DLR, PSI and U. Winnipeg. All samples are <10 mm. Spectra from all labs show the same spectral features, indicating good agreement; offsets in spectra are likely due to differences in packing; also, the DLR measurements were made under vacuum while these PSI and Winnipeg measurements were made under ambient conditions (could be responsible for differences in water bands). Deep-UV measurements from PSI and LASP, and MIR measurements from DLR are not shown here.

materials remotely. In 2020, the facility will be upgraded to allow for the measurement of ice-mineral mixtures at the extreme temperatures of space (-193 °C). Measurements of ice-mineral mixtures will have direct ISRU applications for future mission planning.

1.1.3. Production of UV Standards

TREX Co-I Greg Holsclaw is working on the UV calibration standard (reflective glass diffuser with platinum coatings), and obtaining an updated quote from a manufacturing vendor to be given to each of the TREX labs for uniform calibration. As a comparison case, Co-I Roger Clark has made four UV standards of gold on aluminum. Clark is





(Top) The TREX UV spectrometer setup at CU LASP. (Bottom) An initial spectral measurement from the LASP lab, of the mineral hematite.

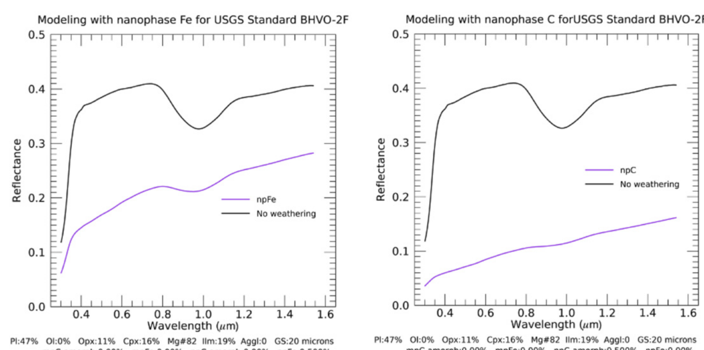
also working on getting quotes for platinum coatings, as platinum is better for use in the UV. As the standards are produced, we intend to distribute them to other labs doing UV measurements for collaborative purposes.

1.2 Lunar and Small Bodies Studies

The TREX lunar and small bodies teams (Themes 2 and 3) have been working in earnest on various studies, a few of which we highlight here. One of the foundational TREX products (effort led by Co-I Rebecca Ghent) will be a Moon grain size map, and that effort is ongoing. In addition to the work outlined below, plans are in progress for solar wind simulations on asteroid-relevant powder minerals, to be performed at Univ. Illinois Urbana-Champaign (UIUC) in early-mid 2020, along with UV-NIR spectral measurements of the irradiated powders.

1.2.1 Space Weathering: Nanophase Fe0 metal vs. Graphite (C)

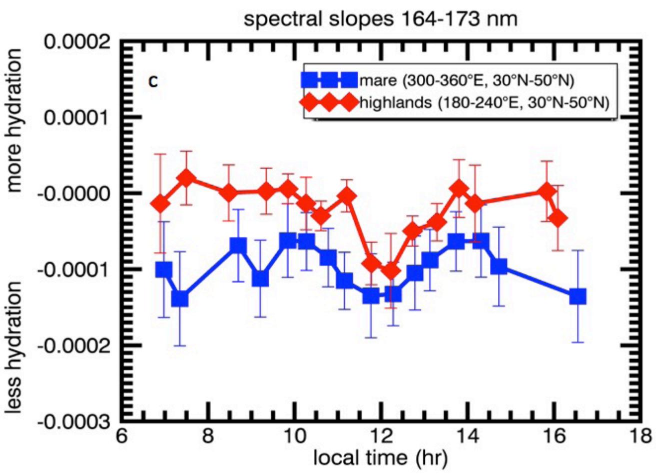
Work led by TREX Co-I Karen Stockstill-Cahill focuses on spectral modeling of space weathering effects. Modeling techniques at visible-near infrared (VNIR) wavelengths can simulate the effects of lunar-like space weathering by metallic iron (Fe^0). Stockstill-Cahill's new work shows that using graphite (in place of Fe^0) results in stronger effects of space weathering. Space weathering of lunar material with Fe^0 lowers the albedo (darkening effect), increases the continuum slope (reddening of spectrum) and attenuate absorption features. Graphite, like Fe^0, is found to redden the slope; graphite is found to lower the albedo more dramatically than Fe^0 and also attenuates absorptions more than Fe^0. Graphite may be an important space weathering product on some types of asteroids.

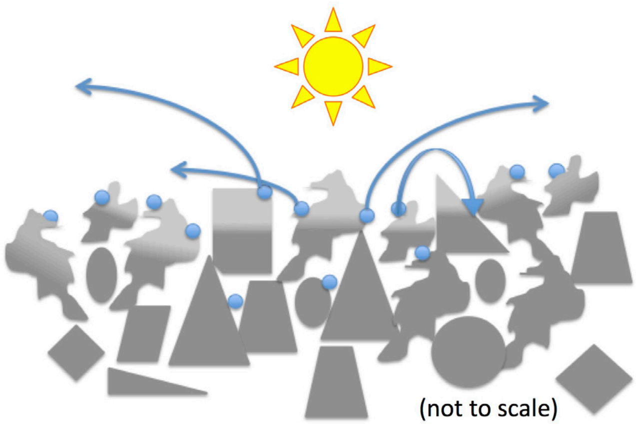


Models demonstrating the spectral effects of simulated space weathering on a silicate-type sample. (left) 0.5% nanophase Fe0 metal; (right) 0.5% nanophase graphite

1.2.2 Diurnally-Migrating Lunar Water: Evidence from Ultraviolet Data

In a collaborative effort with the DREAM2 team, Hendrix et al. (Geophys. Res. Lett., Feb 2019) used data from the Lunar Reconnaissance Orbiter's Lyman Alpha Mapping Project (LAMP) to uncover the temporally-varying spectral



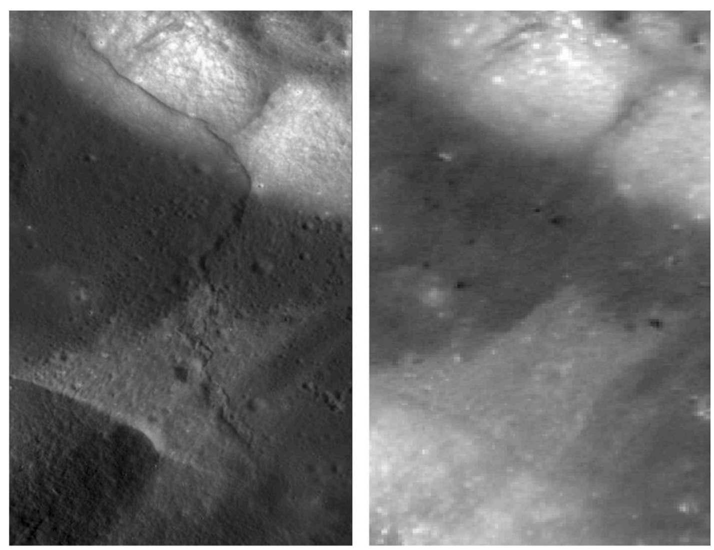


(Top) Spectral slopes measured by LRO LAMP vary throughout the day, particularly near noon for highlands regions. The change in slope is interpreted as due to a loss of hydration due to thermal desorption. (Bottom) This cartoon representation shows how water molecules are sparsely attached to some grains at the top of the lunar surface and desorb near local noon.

characteristics of adsorbing and desorbing water throughout the lunar day. Hendrix et al. presented a model wherein water molecules are tightly bound to the grains at the top of the lunar regolith until surface temperatures reach their peak near local noon. Near local noon, the molecules thermally desorb and can move to a nearby location that is cold enough for the molecule to be stable, perhaps into the small shadow cast by a neighboring grain. The lunar grains are rough (and shaped irregularly), which may be related to how the molecules can remain tightly bound for much of the lunar day.

1.2.3 Optical Maturity (OMAT) Results Inform Lunar Exploration

The lunar farside near South Pole Aitken Basin (SPA) remains an area of keen interest for lunar exploration. Optical maturity (OMAT) studies undertaken by JA Grier, show that the ejecta from optically fresh rayed craters is interacting with swirls. However, the relatively small areal extent, depth, and expected volume of immature ejecta would suggest that if such craters are 'feeding' swirls, this is not a dramatic or necessary effect for the existence of swirls. Understanding how blocks/boulders relate to the optical maturity of crater ejecta is key to unlocking refreshing mechanisms as well as gaining insight into grain/particle/block sizes associated with fresh craters. This informs our understanding of the small/midscale roughness of the regolith. Finally, examination of the optical maturity of the area(s) in and around lunar lobate scarps has offered unexpected results. No bright OMAT signature has been detected, although such a signature is almost always present near topographic expressions such as peaks and crater rims. This may suggest that whatever is 'resetting' the crater densities around lobate scarps is also resetting the optical maturity. Another possibility is that the lobate scarps possess a profile that is too gentle/smooth to promote the OMAT refreshing seen in steeper topography.



Left: LROC image of Lee Lincoln scarp. On the right, the same area in OMAT. Note that there is no suggestion of a bright/immature signature associated with the scarp (Banks, et al., 2019).

1.2.4 Initial Ryugu Results

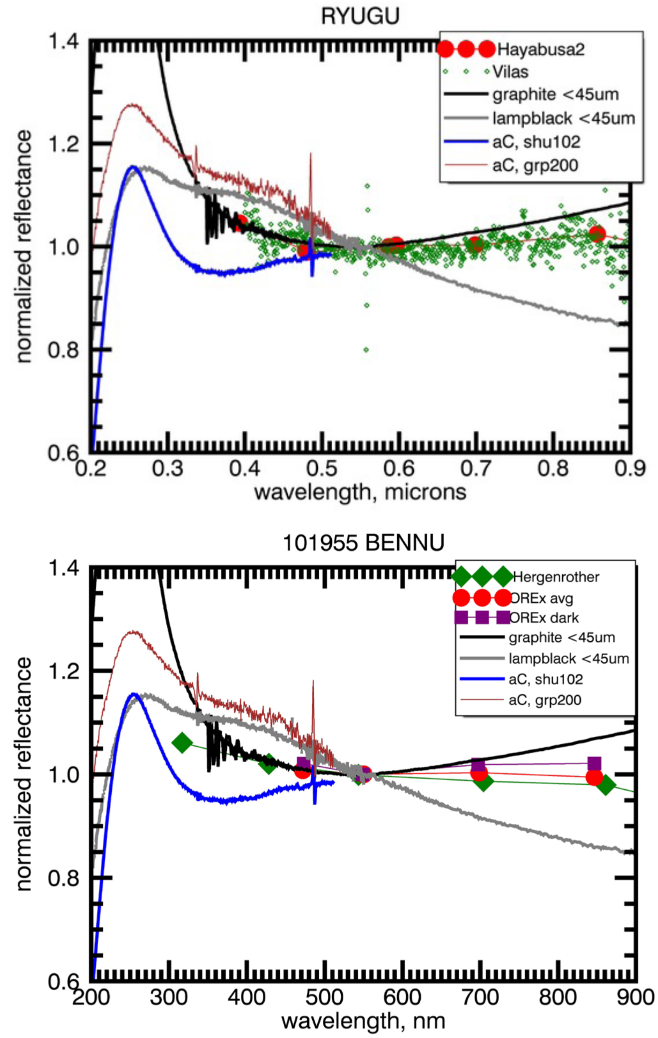
TREX investigator Deborah Domingue, as a Hayabusa2 team member, brings first-hand knowledge of the interesting NEA Ryugu to the TREX team; this involvement will allow for direct comparisons between TREX laboratory data and Hayabusa2 datasets of this fascinating body. Dr. Domingue participated in photometric characterization of potential sample collection sites and contributed photometric analysis and standardization for examining color properties across the surface and tools for extracting color spectra from images. Dr. Domingue co-authored the science papers covering the initial results from Ryugu, published in Science.

1.2.5 C-Complex Asteroids: UV-Visible Characteristics & Links with Space Weathering

TREX investigators Amanda Hendrix and Faith Vilas have completed a thorough investigation of the UV-visible spectral characteristics of C-complex asteroids, based on existing datasets from ground-based telescopes combined with data from the International Ultraviolet Explorer and Hubble Space Telescope. Their analyses found that, though C-complex asteroids are typically rather spectrally bland at VNIR wavelengths (with the exception

> TREX studies of low-albedo class asteroids, including near-Earth asteroids Bennu and Ryugu, highlight the importance of space weathering effects in controlling the surface composition, as shown in UV-visible spectral characteristics.

of the 0.7 micron feature that often appears), all bodies in their study exhibit a UV absorption edge near 400 nm, typically attributed to an iron charge transfer feature due to the presence of phyllosilicates. Hendrix and Vilas showed that the UV absorption is not necessarily linked to taxonomic sub-type within the C complex and that the absorption is nearly always weaker in the asteroids than in carbonaceous chondrites -- a clue that space weathering could be linked. Comparisons with laboratory data of mixtures and opaques such as carbons and irons showed that increasing amounts of opaque weaken the UV absorption. Because numerous laboratory studies have shown that such opaques are likely products of weathering processes, Hendrix and Vilas concluded that carbons, such as amorphous or graphitized carbon, are likely to be present on the surfaces of many of these C complex asteroids (as weathering products) and that they



Carbons could be responsible for the UV upturns seen in the spectra of Bennu and Ryugu (from Hendrix and Vilas, 2019).

can be present in relatively small abundances and still provide a darkening effect and a weakening of the UV absorption. They showed that the unusual "blue" spectral shapes of Bennu and Ryugu are likely due to graphitized carbons on the surfaces, the result of intense surface processing during inner Solar System passes.

1.3 TREX Fieldwork Preparations

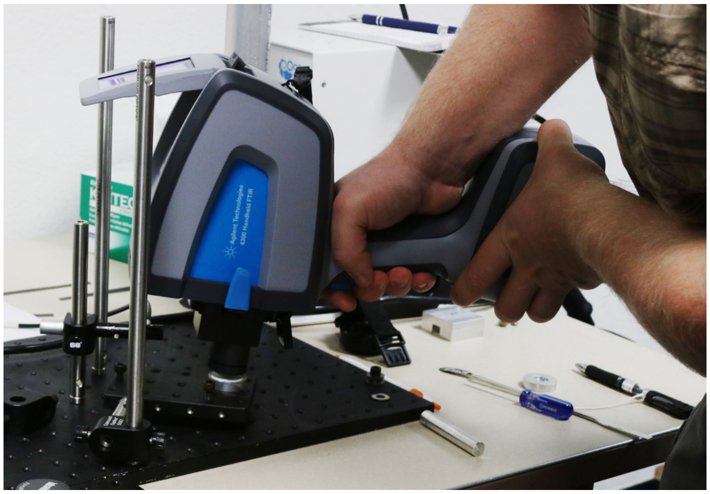
TREX fieldwork in years 3 and 4 (2020 and 2021) in fine-particulate environments will utilize a rover (Zoë) fitted with remote sensing instruments and decision-making software. The remote-sensing suite will cover spectral ranges from the UV through MIR (~0.2 – 15 mm), plus gamma ray/neutron and Raman spectrometers and an XRD. Throughout this wide optical spectral range, there are features that will inform us about hydration state, mineralogy, and particle size. This knowledge will offer insight into ISRU potential.

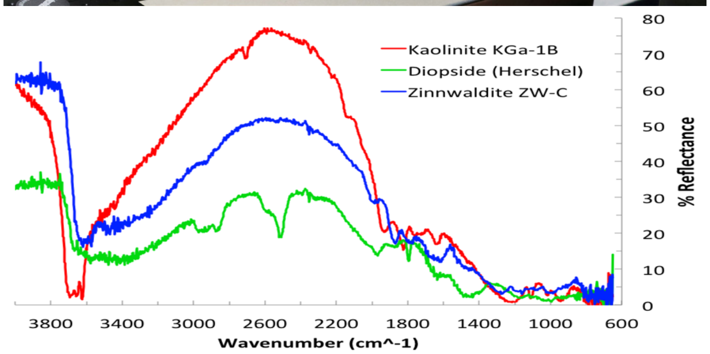
Preparations for field testing of autonomous rover operations have been picking up speed this year! The TREX team is planning field work in April/May of 2020, in Hopi Buttes Volcanic Field (AZ) and Yellow Cat (UT) (see Figures below). Theme lead Eldar Noe Dobrea performed a scouting trip to the three field sites to identify locations for rover operations. He was accompanied by Neil Pearson at Hopi Buttes, Roger Clark at Yellow Cat, and David Gaylord at Palouse. Multiple locations were identified and documented on the basis of accessibility, vegetation cover, scientific interest, and operational scenarios. Noe Dobrea accompanied David Wettergreen on an NSF funded project to Cuprite to test Zoe's new exploration strategy. Tom Prettyman visited Lava River Cave near Tucson AZ and made gamma ray measurements, using his newly-developed field GRS, in and around the cave to characterize local geochemistry.

(Top) Colorfully layered phyllosilicate-rich units seen in this drone view present an easily navigable fine-grained environment in the Yellow Cat field site, where we will test next-generation rover operations. (Middle) TREX Team member Roger Clark explores a poorly vegetated terrain in the Yellow Cat site. (Bottom) TREX team member Neal Pearson prepares the Agilent FTIR to perform in-situ measurements at the Hopi field site during a scouting trip identify sites for testing next-generation rover operations in the field.

The rover Zoë's spectrometer (ASD FieldSpec Pro) is fully operational (Co-I Wettergreen) on the new pan/tilt mechanism. The robot is able to collect spectra individually, but also panoramas of a specified FOV or dense sampling within a "box" on the ground. Automatic white calibration occurs periodically. The Theme 1 laboratory data of terrestrial samples is in the process of being loaded into the Tetracorder software for real-time use in the field. Co-I Roger Clark has been upgrading the Tetracordrer single spectrum mode to have the software continuously monitor a file so when input comes in, it immediately analyzes it. Co-I Greg Holsclaw (CU/LASP) has purchased the Ocean Optics UV instrument for the field. The TREX team recently acquired a handheld Agilent 4300 FTIR to take into the field to acquire the near-IR to mid-IR data (4000 to 650 cm^{-1}; 2.5 to 15.3 um). In 2019, we calibrated and tested it in the lab on our TREX fine-particulate samples. Preliminary spectra look great

An eruptive center at the Hopi Buttes showing a fissure (Top) and associated pyroclastic deposits (Bottom). The accessibility of the fissure and its interior, the slow wasting of the rocks to fine-grained material, and moon-like landforms makes this an attractive site to test next-generation autonomous rover operations.





Spectra of <10-um samples acquired in the lab (~1 atm) with the Agilent FTIR. Fundamental bands in the ~800-1200 cm-1 region shrink with decreasing particle size

(see figure below). Co-I Melissa Lane coordinated with Wettergreen on FTIR data transfer to the rover and with Co-I Roger Clark on the intelligent system for TIR data.

1.4 Carbon in the Solar System Workshops

TREXers Amanda Hendrix and Faith Vilas continued their organization of Carbon in the Solar System Workshops in 2019, with three events.

- LPSC lunchtime workshop, focus: Darkening Agents in Low-Albedo Materials; kickoff talk by Larry Nittler
- DPS workshop; kickoff talks by Gianrico Filacchione and Lucille LeCorre
- AGU poster session

These workshops have been well-attended and have fostered stimulating discussions and collaborations. We expect to continue them in 2020.

2. Inter-team/International Collaborations

TREX PI Hendrix and DPI Vilas teamed with DREAM2 members Farrell and Hurley on analyses and publication of LRO LAMP data (*Hendrix et al., GRL, Feb 2019*, DOI 10.1029/2018GL081821)

TREX Co-I Grier began working with a research group including VORTICES postdoc Richardson (PSI/VORTICES) and VORTICES PI Rivkin. Richardson (with assistance from Grier) has been using data from citizen scientists to study the effects of incidence angle on crater counts on the Moon, and to ascertain those angles at which the most complete counts are performed. The project also compares this data to previous work done by expert crater counters, who have noted this same effect of incidence angle on count statistics. Once the project has finished with lunar data, Richardson will move on to examining the count data of Vesta.

TREX Co-I Maria Banks began initial discussion with GEODES PI Nick Schmerr. They are planning a collaboration to combine Banks work with lunar lobate scarps with physical and seismic models to assess hazards for future landed missions.

Australia SSERVI team member Gretchen Benedix has joined TREX as a Collaborator, and we have opened discussions about future possible coordination of TREX field studies at international locations.

3. Public Engagement

Guest Curator at the New Mexico Museum of Natural History and Science

Tom Prettyman curated a temporary exhibit on the NASA Dawn Mission for the New Mexico Museum of Natural History and Science (NMMNHS) in Albuquerque. The exhibit features photographs, maps and 3-D images, providing a spectacular, up-close look at Vesta and Ceres. Large, detailed wall panels tell the story of how the Solar System formed and highlight key features of the main asteroid belt. The exhibit includes a scale model of the Dawn spacecraft as well as a description of its innovative ion propulsion system. A shape model of Vesta and

Panoramic view of the Dawn exhibit at the New Mexico Museum of Natural History and Science.

meteorites representative of Vesta and Ceres are also on display. The exhibit closed on 7-July 2019 after a nearly two-year run, the longest of any temporary exhibit by the NMMNHS Space Science Department. Since its opening on 1-Sep 2017, the exhibit has been viewed by nearly 500,000 visitors from all over the world.

June 22, Tom Prettyman gave an outreach presentation – "*Exploring the Main Asteroid Belt: Vistas of Vesta/ Ceres and Visions of Psyche*," hosted by the Albuquerque Astronomical Association.

June 30, Tom Prettyman participated in Asteroid Day – hosted an "Asteroid Advice Booth" at the NMMNHS Dawn Exhibit. *Xanthe Miller's* Albuquerque Alibi advertisement describes the event: "It's never too early to start planning for your last moments on Earth, so zoom over to Asteroid Day. This event rocks the New Mexico Museum of Natural History and Science from 10am to 2pm on Sunday, June 30. Learn about asteroids and their impacts on Earth, NASA's mission to our local asteroid belt, the disappearance of the dinosaurs and other space news. Watch live streaming of other Asteroid Day celebrations worldwide (yes, that's a thing). UNM's Institute of Meteoritics helps visitors distinguish between meteorites and regular, old Earth rocks and the curator of the exhibition, Dr. Tom Prettyman, hosts an Asteroid Advice Booth." (https://alibi.com/events/307981/Asteroid-Day.html)

Apollo 11 Anniversary Events

July 18 – Sanlyn Buxner and Maria Banks participated in NASA's Apollo 50th Anniversary Outreach events on the National Mall in Washington DC.

Sanlyn Buxner, along with PSI high school volunteer, Macey Brown, engaged the public in lunar landing activity and talked about how TREX is preparing for future lunar exploration.

July 20 – Sanlyn Buxner participated in NASA Apollo 50th Anniversary event at the Arizona-Sonora Desert Museum in Tucson, AZ. Along with PSI volunteers, Maya Bakerman and Mark Morris, engaged visitors in lunar landing activity and talked about how TREX is preparing for future lunar exploration.

July 20 and 21, Ryan Watkins was featured presenter at Lunar Block Party at the Museum of Flight in Seattle, WA. She also engaged visitors with 3D models and images of the lunar surface in talking about current and future exploration.

Other Events

November 21, Tom Prettyman gave the Sigma Xi Distinguished Public Lecture: "From the Beginning of Time to the Center of the Earth: How Robotic Exploration Shapes Our View of the Solar System," hosted by the University of New Mexico chapter.

December 14, Eldar Noe Dobrea and Sanlyn Buxner trained Galaxy Explorers, teen docents, at Chabot Space & Science Center in Oakland, CA. Eldar gave a one hour presentation on STEM careers and TREX related science. Sanlyn Buxner spent 1.5 hours engaging teens in outreach activities that docents can use on the floor interpreting for the public.

Macey Brown and Sanlyn Buxner

Macey Brown demonstrating the resolution of images used to pick lunar landing spots

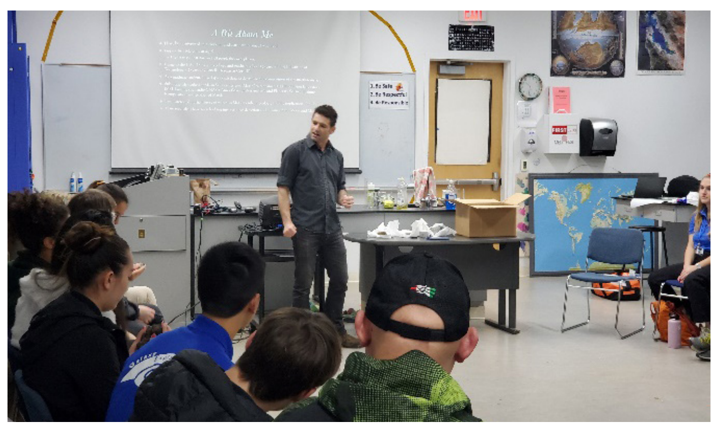
July 18, Amanda Hendrix gives a keynote presentation at the Apollopalooza Celebration at the Wings Over the Rockies Air & Space Museum in Denver, CO.

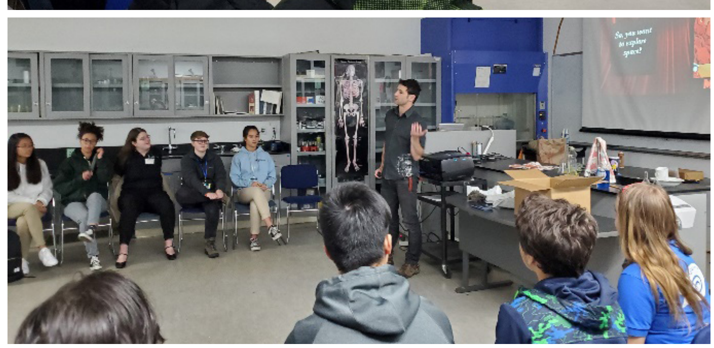
Maya Bakerman and Mark Morris talk to visitors at the Arizona-Sonora Desert Museum about the history of lunar exploration

Jennifer Grier attended the World Science Fiction Convention called WorldCon Dublin 2019 (August) and moderated panels, including the panel "Keeping the Show on the Road, Low Earth Orbit and Beyond," in which some of the basic concepts, resources, and needs around a sustainable human presence on the Moon (i.e. dust, particle size, potential hazards, etc.) were discussed.

Amanda Hendrix and colleagues in Boulder CO held planetary outreach events at six Boulder County Farmers Markets.

Boulder SSERVI PIs Amanda Hendrix and Alex Parker (ESPRESSO) staff an outreach event at the Boulder County Farmers Market.



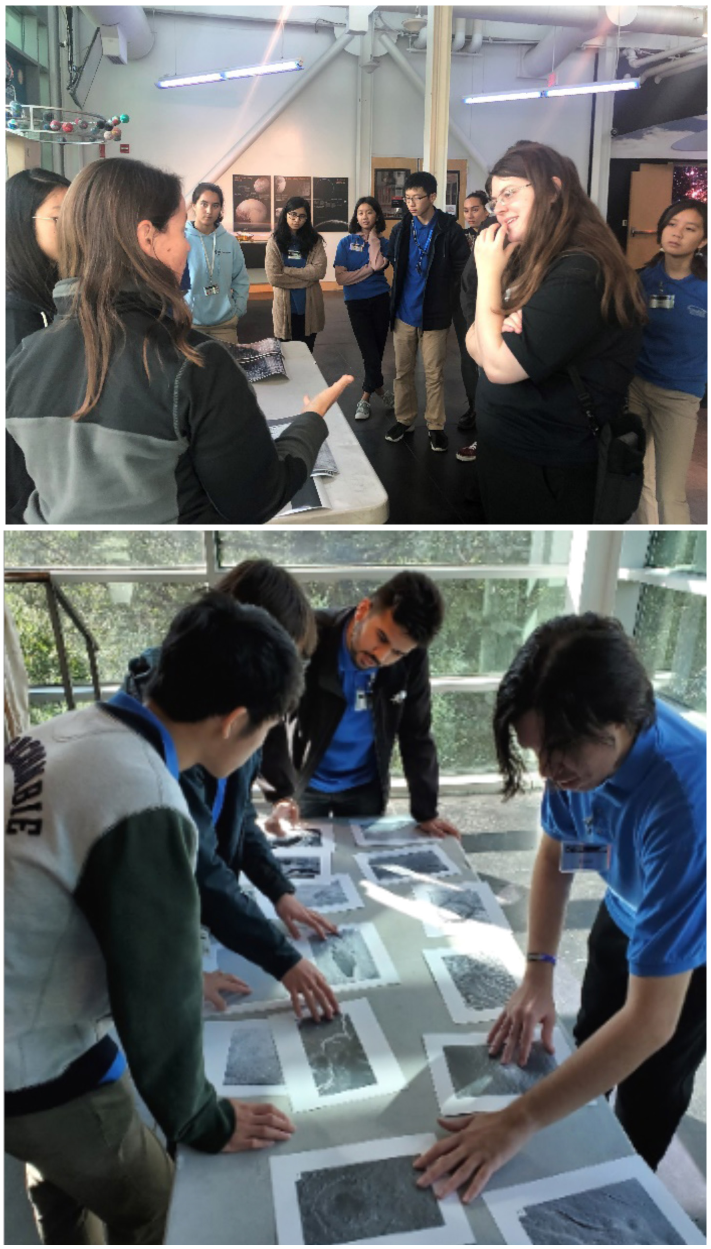


TREX scientist Eldar Noe Dobrea giving a talk for the Galaxy Explorers.

4. Student/Early Career Participation

Undergraduate Students

1. Brent Lorin, Johns Hopkins University, Whiting School of Engineering
2. Christian Cooper, Brown University, Department of Earth, Environmental, and Planetary Sciences
3. Rebecca A. Carmack, Purdue Univ., Planetary Science
4. Destry Monk, Univ. Colorado, Physics



Sanlyn Buxner works with the Galaxy Explorers leading them through lunar themed activities to use with the public.

Graduate Students

1. Alberto Candela, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.6. Srinivas Vijayarangan, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.
2. Kevin Edelson, Ph.D. Candidate, Robotics Institute, School of Computer Science, Carnegie Mellon Univ.
3. Camilo Jaramillo, Pennsylvania State Univ.
4. Eric Lang, Nuclear, Plasma, and Radiological Engineering Department, Univ. Illinois at Urbana-Champaign.
5. Jess Mollerup, Western Washington Univ.

Post-doctoral Researchers

1. Caroline Ytsma, Mount Holyoke College.

New Faculty Members

1. Dr. Ruitian Zhang, Columbia Univ.

5. Mission Involvement

1. **Lunar Reconnaissance Mission (LRO)**, Noah Petro, Deputy Project Scientist, LROC, Diviner, LOLA; Amanda Hendrix LAMP Co-I; Maria Banks, LROC, Project Office: Science Data Manager; Rebecca Ghent, Diviner; Ryan Clegg-Watkins, LROC; Faith Vilas, LAMP Co-I.
2. **Ceres mission concept study** - Amanda Hendrix, Tom Prettyman, Lynnae Quick.

TREX undergraduate student Christian Cooper gives a talk at the LPI Intern Symposium.

3. **MoonRanger** (CLPS LSITP payload): David Wettergreen - rover development as Co-I.

4. **ExoMars Trace Gas Orbiter**, Ed Cloutis, Co-I on NOMAD and ISM instruments.

5. **OSIRIS-REx**, Ed Cloutis; Rebecca Ghent; Jian-Yang Li.

6. **Mars Reconnaissance Orbiter (MRO)**: Maria Banks - High Resolution Imagining Science Experiment (HiRISE), Science team member, collaborator; Roger Clark - CRISM Co-I.

7. **Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) Mission**: Maria Banks - Science team member, collaborator.

8. **Io:** The Next Generation (proposed mission concept study) - Amy Barr-Mlinar, Co-I.

9. **Hayabusa 2**, Faith Vilas, Deborah Domingue, Jorn Helbert.

10. **Blue Origin** - Ryan Watkins serves on Science Advisory Board and provides feedback regarding landing site selection and hazard analysis, as well as lunar-science related goals.

11. **NASA International Space Station**, EMIT, Roger Clark: Co-I.

12. **NASA SBIR,** Lunar Exploration Gas Spectrometer (LEGS), Roger Clark: Co-I.

13. **Psyche** - Tom Prettyman, Co-I, Light Elements Lead/ Gamma-Ray and Neutron Spectrometer Team.

14. **LunaH-Map** - Tom Prettyman, Co-I

15. **Oracle** - proposed Themis tour mission concept - Tom Prettyman, Co-I (Led by Margaret Landis)

6. Awards

TREX Co-I Ryan Watkins was announced as a member of Blue Origin's Science Advisory Board for the Blue Moon lunar lander project.

TREX Co-I Melissa Lane was named a Fellow of the Mineralogical Society of America! As TREX Theme 1 lead, Melissa coordinates the TREX lab experiments.

TREX Deputy PI Faith Vilas was named the editor of the Planetary Science Journal.

TREX Deputy PI Faith Vilas was awarded the Whipple Award at the AGU meeting in San Francisco. Her talk was entitled "Synergy in Planetary Science From the Ground Up."

SSERVI INTERNATIONAL PARTNERSHIPS

SUMMARY OF INTERNATIONAL ACTIVITIES

SSERVI's International Partnerships Program provides collaboration opportunities for researchers within the global planetary science and human exploration community, working both on development of new science and technical approaches and communicating this science to the public. International partners are invited to participate in all aspects of the Institute's activities and programs. In addition, SSERVI's Solar System Treks Project (SSTP) has played a significant role in the institute's international partnerships and collaborative efforts are outlined in the sections below.

Non-U.S. science organizations can propose to become either Associate or Affiliate partners of SSERVI on a no-exchange-of-funds basis. Affiliate partnerships are with non-government institutions (e.g., universities and other research institutions); the majority of existing SSERVI international partnerships are Affiliate. Associate partnerships are government-to-government agreements including those between NASA and international space agencies.

In 2019, JAXA was welcomed as SSERVI's newest Associate International Partner. They join the 10 previously signed partnerships which include: Australia, Canada, France, Germany, Israel, Italy, Netherlands, Saudi Arabia, South Korea, and the United Kingdom. Discussions have also continued with representatives from the Mexican Space Agencies on development of a proposal for membership.

Below is a summary of the collaborations between SSERVI and the International Partners, followed by reports from some of the partners.

JAPAN - New Partners!

SSERVI and the new JAXA partners built upon ongoing collaborations and activities. NASA's Science Mission Directorate and JAXA jointly requested that SSTP develop a data visualization and analysis portal for Mars' moon Phobos to be used for Japan's upcoming Martian Moons eXploration (MMX) mission. SSTP produced and demonstrated a prototype portal and are working with the international Phobos/Deimos working group to identify and integrate data desired to support this mission.

After demonstrations of SSTP capabilities at the 2018 JpGU Conference in Chiba, Japan, SSTP was approached by the project scientist for the JAXA/ESA BepiColombo mission to Mercury and asked if we could develop a portal using Messenger data for use in BepiColombo mission planning. SSTP was also approached by members of the Hayabusa 2 mission and asked if SSTP could develop a portal for visualization and analysis of data returned from Ryugu. These questions were referred to the NASA Chief Scientist and the Director General of JAXA, both in attendance at the conference, and a joint decision by both agencies was made to proceed with collaborations for both missions. Thus, SSTP produced the new Mercury Trek portal which was formally released during the November 11, 2019 transit of Mercury and with BepiColombo now en route to Mercury. A new release of Mercury Trek is in development and is scheduled for release in spring of 2020. This will include integration of additional data products and implementation of interface controls in Japanese as well as English. SSTP also produced a prototype of the Ryugu portal for demonstration at the JAXA-SSERVI partnership ceremony. SSTP is working with JAXA to integrate newer -high-resolution Hayabusa2 data into the Ryugu prototype and advance it to a released portal in 2020.

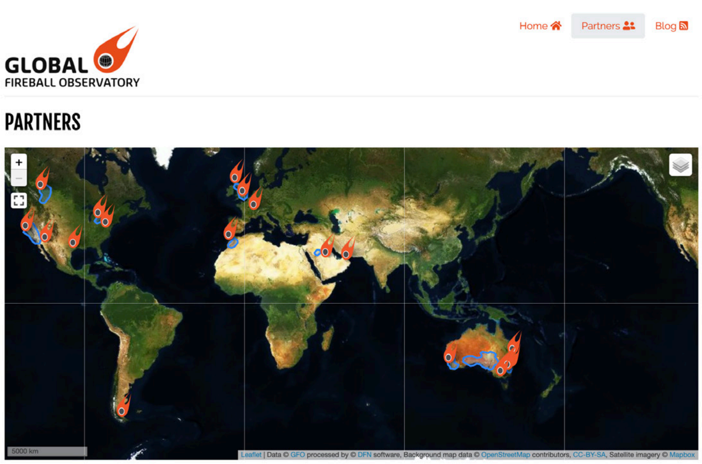
In addition, another area of collaboration with JAXA is through public engagement. This year JAXA BepiColombo Project Scientist Go Murakami contributed a recorded video presentation along with B-roll footage that was integrated into SSERVI's public program for the Mercury transit and release of Mercury Trek held at the Frost Museum of Science in Miami.

For over 8 years SSERVI has been an active member of RoboRave International, serving as invited keynote speakers, competition judges, and partnership facilitators. At this year's 5th RoboRave in Kaga City, the official partnership between SSERVI and JAXA (signed July 2019) facilitated an expanded role in developing the robotics workshop, with the creation of two new events--an education round table and an Industry Day event. SSERVI coordinated and co-planned these events along with JAXA, the Mayor of Kaga City, and key government officials. SSERVI's invitation for JAXA to participate was such a success that JAXA subsequently agreed to sponsor future RoboRaves in Kaga City.

AUSTRALIA

SSERVI's Australian partner, Curtin University, is in the process of expanding its Desert Fireball Network beyond the Australian Outback into new locations around the world. SSERVI's Central Office is working with Curtin to facilitate the expansion of the Desert Fireball Network into the Global Fireball Observatory (GFO). SSERVI Central has facilitated the expansion of the network into the state of Nevada this year. We also leveraged our developing relationship with the Mexican Space Agency (AEM) to facilitate installation of new GFO stations on the site of Mexico's National Astronomical Observatory in Baja California and at several locations throughout the Sonoran Desert.

As SSERVI Central works to help the expansion of our Australian partner's Desert Fireball Network to the Global Fireball Observatory, we are also assisting in dissemination and integration of their related outreach



Picture/screenshot from GFO homepage (https://gfo.rocks/partners.html)

efforts. We highlighted the Fireballs in the Sky curricula developed through Curtin University at a variety of NASA booth venues including AGU and the American Library Association, and are integrating the Fireball Network's Fireballs in the Sky augmented reality app into NASA's citizen science program. SSERVI staff has also integrated Fireballs in the Sky into the Astromaterials Certification Workshops they conduct, certifying K-12 educators to borrow NASA meteorite and Apollo lunar samples for study in their classrooms.

Additionally, following the largest-ever space resources meeting in Luxembourg in October 2019, Greg Schmidt was invited to give a talk on SSERVI and potential ISRU collaborations by Professor Andrew Dempster, the director of the Australian Centre for Space Engineering Research (ACSER). This talk and subsequent discussions opened a new avenue of collaboration in this important area by the Australian space community and SSERVI, with planned follow-ups at an ACSER visit to Ames and a side meeting of the 2020 COSPAR meeting in Sydney.

CANADA

SSERVI's Canadian PI, Dr. Gordon Osinski, continued the development of the Institute for Earth and Space Exploration (www.space.uwo.ca) at Western University this year. It replaced the Center for Planetary Science and Exploration, which was established as the first SSERVI international partnership in 2008. CPSX galvanized support on-campus in the area of planetary science and exploration. They recruited faculty, built Canada's only graduate program in this area, spearheaded outreach and education, and have many notable successes to show for this a decade on.

SSERVI again provided support for the Sudbury Field School in 2019 through support of several US students to attend.

ITALY

SSERVI's Italian partners play a leading role in laser retroreflector science and development. SSTP partnered with our Italian colleagues at INFN to implement a new lunar retroreflector planning tool that has been integrated into Moon Trek and presented at various scientific conferences. SSERVI and SSTP collaborated on several symposia and public events in 2019. A summary of these activities can be found in the SSERVI Central Office Public Engagement section of this report. (See pages 164, 165)

FRANCE

SSTP is in the early stages of a collaboration with SSERVI's French partner in characterizing multiple potential lunar traverse possibilities. In this collaboration, analysis of sites of interest to the French team will serve as test cases for new high-resolution data products being generated by a new SSTP pipeline as well as new international data products being ingested into Moon Trek.

KOREA

SSTP continues to work with the South Korean Space Agency (KARI) and its partner, the Korea Institute of Geoscience and Mineral Resources (KIGAM). This year, the joint efforts have largely focused on ingestion and integration of specialized maps developed by the lead for the gamma ray spectrometer that is being built for the Korea Pathfinder Lunar Orbiter (KPLO). SSTP is also working with KARI to investigate the applicability of using the Moon Trek portal as a testbed for their terrain-relative navigation development efforts.

KARI recognizes the vital role outreach will play in the upcoming KPLO mission as well as the experience that SSERVI staff has in conducting E/PO for past lunar missions. They have engaged SSERVI Central staff in initial discussions of outreach strategies and planning for KPLO. SSERVI Central has responded with a variety of ideas and has instituted discussions with both KARI and the Goldstone Apple Valley Radio Telescope program to potentially use one or more 34-m Goldstone DSN dishes in a participatory campaign modeled after the successful LCROSS Student Telemetry Team.

UNITED KINGDOM

SSERVI joined with its partners in the United Kingdom to host the 7th European Lunar Symposium from May 21-23, 2019 in Manchester, UK.. This meeting built upon the European Lunar Symposiums (ELS) held in Berlin (2012), London (2014), Frascati (2015), Amsterdam (2016), Muenster (2017) and Toulouse (2018), as well as the global interest in new missions to the Moon. The meeting was held under the umbrella of the European SSERVI teams, supported by the local team at Manchester and SSERVI colleagues.

The format was similar to previous European Lunar Symposiums and consisted of both oral and poster presentations divided into four broad themes of: "Science of the Moon," "Science on the Moon," "Science from the Moon," and "Future Lunar Missions." A total of 94 presentations were made over two and a half days (58 orals + 36 posters). Approximately 130 participants, representing the global community of lunar scientists and explorers, made this a highly successful event.

Development of new Partnerships:

MEXICO

At the 2019 meeting of the International Astronautical Congress, SSERVI management met with Dr. Salvador Landeros Ayala, the new incoming Director of AEM and Dr. Gustavo Medina Tanco, who plays a leading role in the development of Mexico's COLMENA lunar micro-rovers scheduled for deployment by Astrobotic's Mission One. In those meetings we initiated discussions about testing the COLMENA rovers in SSERVI's Lunar Regolith Simulant Testbed.


ELS 2019 Group Photo
credit: ELS organizers

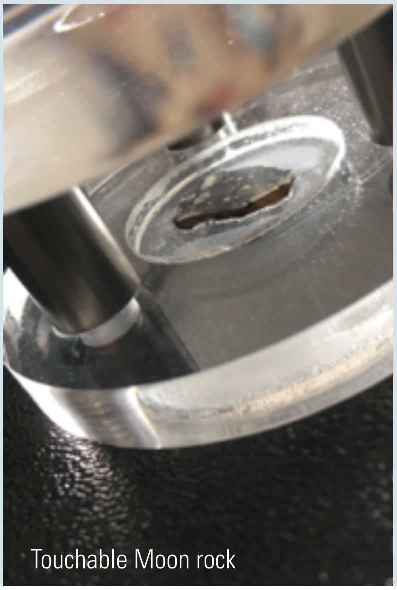
2019 ITALY PARTNERSHIP HIGHLIGHTS

During 2019, SSERVI joined with their Italian partners to co-host four meetings and events focused on planetary science research, innovation, and celebrating the Apollo 11 50th anniversary. These were coordinated between SSERVI, NASA Ames, ASI, INFN and the Italian Consul General in San Francisco, California.

Apollo 11 Anniversary in Rovereto, Italy

The Fondazione Museo Civico di Rovereto in Rovereto, Italy, part of the Italian node of SSERVI, arranged an exhibition to celebrate the Apollo 11 landing on the Moon. They were supported by ASI and national and international partners. Emily Law represented SSERVI, SSTP and JPL as a guest speaker at the event on May 18, 2019. SSERVI also put together a twelve minute video on past and future lunar landing sites for the event. The video uses Moon Trek to visit each of the Apollo landing sites. It then looks ahead and visits potential future landing sites identified at the Lunar Science for Landed Missions workshop held at NASA Ames Research Center in 2018. SSERVI/SSTP also provided the exhibit with a touchable Moon rock.

On May 18th, 2019, spent Saturday night talking about the past, present and future of Solar System exploration.



Touchable Moon rock

Co-hosted Symposium with the Italian Consulate of San Francisco

On Tuesday, June 4 the Consul General of Italy along with SSERVI came together at NASA Ames Research Center for a joint celebration of the city of Matera, the Italian hub for space science and technology and the "2019 European Capital of Culture." On the occasion of the 'Italian Republic Day' in San Francisco, and in the framework of the consolidated Italian partnership with SSERVI, the Italian Consulate and Ames gathered their respective cultural and space communities to celebrate the unique city of Matera, foster joint cultural and research activities and, ultimately, promote closer Italian-American cooperation.

The Italian Consul General, Lorenzo Ortona, in San Francisco speaking of Matera on June 4, 2019 at NASA Ames Research Center.

Visit by ASI President to NASA Ames Research Center

Giorgio Saccoccia, president of the Italian Space Agency, "Angenzia Spaziale Italiana" (ASI) visited NASA Ames on August 8, 2019 in further discussion of related research and technical interests. SSERVI met with the president and provided a keynote speech related to the partnership between SSERVI, INFN and ASI.

President of Italian Space Agency visits Ames on Aug 8th (from left to right): Aga Goodsell (NASA-ARC), Giorgio Saccoccia, President, Italian Space Agency (ASI), Sabrina Corpino (Polytechnic University of Turin), Eugene Tu, Director, NASA Ames Research Center (NASA-ARC), Simone Dell'Agnello, Science Attache, Italian Consulate General, San Francisco.

US–Italy Innovation Forum Space Round Table on October 18th

SSERVI hosted a roundtable at NASA Ames on October 18, 2019 with the President of ASI as part of an ITALY-USA Innovation Forum held for the visit of the President of the Italian Republic to San Francisco and Silicon Valley, Sergio Mattarella. Moderators included Giorgio Saccoccia (ASI), Carol Carroll (NASA-ARC), Angelo Fontana (Avio), and Greg Schmidt (SSERVI). Presentations included an overview of NASA's ARTEMIS and NASA's Commercial Lunar Programs from Carol Carroll, Ames Deputy Center Director, and talks by Simone Dell'Agnello, Science Attache, Italian Consulate General, Giorgio Saccoccia, President, Italian Space Agency (ASI), Donato Amoroso, CEO, Thales Alenia Space Italy, Richard DalBello, Vice President of Business Development & Government Affairs, Virgin Galactic, Simone D'Amico, Director of Space Rendezvous Laboratory, Stanford University, and Greg Schmidt, Director, SSERVI. A roundtable discussion followed with representatives discussing three topics; Aerospace Commerce, Particle Astrophysics, and Earth Science. The event also included a video presentation from SpaceX.

SSERVI Director Greg Schmidt presented Giorgio Saccoccia, President of the Italian Space Agency (ASI), with a meteorite. Photo credit: Joe Minafra.

From left to right: Angelo Fontana, VP Marketing & Business Development, AVIO, Donato Amoroso, CEO, Thales Alenia Space Italy, Giorgio Saccoccia, President, Italian Space Agency (ASI), Carol Carrol, Ames Deputy Center Director, Greg Schmidt, Director, Solar System Exploration Research Virtual Institute, and Simone Dell'Agnello, Science Attache, Italian Consulate General, San Francisco.

1. Australia 2019 Report

It has been a huge year for planetary science in Australia. The community has contributed to missions ranging from Mars MSL Curiosity, to BepiColombo, to OSIRIS-Rex, and Hayabusa 2. Australian scientists have been working with Chinese colleagues to ensure that samples returned by Chang'e 5 and Chang'e 6 are made available to the international community. And as the enthusiasm for all things 'space' generated by the inauguration of the Australian Space Agency in 2018 continues, Australian planetary scientists are considering for the first time what contributions they can make to payloads flown by other agencies, or to small home-grown Australian missions. Issues remain. The research environment in Australia is uniquely challenging. It is still not recognized that there is a virtuous circle connecting blue sky research and engineering in planetary and space science, to the success of national agencies, and growth in the space sector. The fact that science underpins innovation in space industries is not understood. Hopefully with the help of our international partners we can continue to make the case at home.

The 2019 Western Australian Scientist of the Year was awarded to Professor Phil Bland (SSERVI AU Director) for recognition as one of the State's finest leaders in science; and Dr. Katarina Miljkovic (SSTC, Curtin) was recognized with the Western Australian Young Tall Poppy Science Award for her exceptional research and passionate

Figure 1: U.S. Secretary of Commerce Wilbur Ross, top left, and Australian Prime Minister Scott Morrison, top right, witness the signing of a letter of intent between NASA (Deputy Administrator, Jim Morhard) and the Australian Space Agency (Head, Dr. Megan Clark AC)

Figure 2: (left) Prof Phil Bland awarded 2019 Western Australian Scientist of the Year. (Right) Dr Katarina Miljkovic wins the Australian Institute of Policy and Science Tall Poppy award.

commitment to communicating science.

John Curtin Distinguished Professor Phil Bland who leads Curtin's Space Science and Technology Center, received $526,000 in ARC funding for The Global Fireball Observatory: Illuminating Solar System Origins, to pinpoint the origins of hundreds of meteorites as part of an international collaboration.

Hadrien Devillepoix, Curtin University is part of an Australian National University-led project that received $632,000 for the research project 'Exploring the Dynamic Universe with DREAMS' through the Australian Research Council LIEF program. Combined with optical observations, DREAMS (Dynamic REd All-Sky Monitoring Survey) will be a valuable tool to determine albedos and likely spectral types of Near-Earth Asteroids.

The Binar [BIN-ah] Space Program from Curtin University, Space Science and Technology Center, continued in

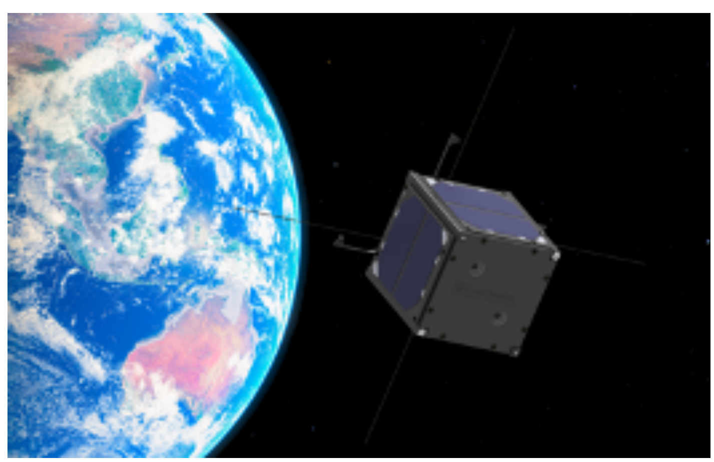


Figure 3: Binar-1small satellite rendered in orbit above Australia.

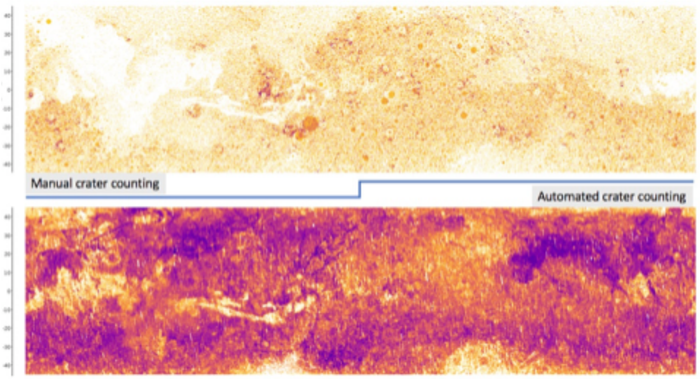


Figure 4: Automated Crater Detection Algorithm, showing a subset of the 94 million craters, Curtin University.

2019 with a focus on the in-house development of an integrated CubeSat bus. The 0.25U unit combines an on-board computer (OBC), electrical power system (EPS), attitude determination system (ADS), attitude control system (ACS) and global positioning system (GPS). The year was spent iterating through 3 major versions and multiple sub-system tests in the new Space Environment Laboratory at Curtin. The year ended with the signing of contracts for two launches with Space-BD, the first at the end of 2020 and the second mid-2021. These two missions will be focused on qualifying the integrated bus.

Another group (Machine Learning in Planetary Science) within the Space Science and Technology Center has developed and trained an automated crater detection algorithm (CDA) based on a convolutional neural network. Initially the algorithm was trained by annotating images of Mars of the controlled Thermal Emission Imaging System (THEMIS) (100m/pix) daytime infrared dataset. The training dataset contains 7,048 craters that the algorithm used as a learning benchmark. The results were validated against the manually counted database as the ground-truth dataset. Our CDA reproduced, within error, the manually compiled database.

> "We have recently extended the CDA to the global ConTeXt Camera (CTX) (5m/pix) mosaic and the algorithm has returned 94,000,000 craters →40 m across the entire surface of Mars."

The project Predictive Analytics for Off-Earth Resource Modelling and Utilization is funded by the CSIRO Space Technology Future Science Platform (FSP). The aim of the project is to support off-Earth and in-situ mining and resource utilization by creating a predictive analytics software platform for off-Earth resource modelling and utilization planning based upon a structured combination of planetary and minor Solar System body data, derived composition models, modelling rules acquired from human experts, and a variety of predictive analytics methods (data mining, machine learning, and predictive modelling).

The core element of the project is the development of three-dimensional resource models analogous to terrestrial mineral deposit block models for off-Earth resources, such as mineral and chemical deposits on or within the Moon, Mars, Mercury, comets, asteroids, and moons of planets in the Solar System.

MINiature Exoplanet Radial Velocity Array. Minerva-Australis facility is a dedicated exoplanet observatory, operated by the University of Southern Queensland, in Queensland, Australia. Officially opened in 2019, it has been gathering data searching for alien worlds, doing follow-up investigations of targets observed by NASA's Transiting Exoplanet Survey Satellite, TESS, and has contributed to the confirmation of 19 TESS planets.

The Australian Center for Astrobiology (ACA) continues to research both the earliest life on Earth, as well as life's adaption and complexification across the great

Figure 5: MINERVA-Australis facility is located at the University of Southern Queensland Mount Kent Observatory.

oxygenation event. Two landmark papers were published in 2019 that highlight the ongoing research on some of Earth's oldest, best preserved life on Earth as preserved in the 3.48 Ga Dresser formation of Western Australia.

2. Inter-team/International Collaborations

2.1 Global Fireball Observatory

The Desert Fireball Network (DFN) uses automated observatories to track the fireballs from space rocks transiting our atmosphere. This has been expanding into the Global Fireball Observatory with cameras across Australia, the USA, England, Scotland, Canada, Saudi Arabia, Morocco, and our first camera is being installed in Argentina. A fireball was observed over Edmonton, Canada on September 1st that was observed by GFO cameras and likely dropped a meteorite. Unfortunately, the search terrain was not favorable and it has yet to be recovered. Seamus Anderson (PhD. candidate) has been researching the ability to use drones in searching for meteorites with the help of neural networks. Patrick Shober (PhD. candidate) identified one of our incoming fireballs as a "mini moon" - it was temporarily captured by the Earth before finally falling through the atmosphere. A meteorite recovered in the fall area is yet to be confirmed as the remnant of this fascinating event.

2.2 International Planetary Research Center in Beijing (China)

Alexander Nemchin (Curtin SSTC) has helped to establish International Planetary Research Center in Beijing (China) with the main aim of giving the international scientific community access to lunar samples expected to be returned by Chinese missions to the Moon in the near future. The current international group includes scientists from Washington University in St. Louis, Notre Dame University and Colorado School of Mines in USA; Manchester University, Free University of Amsterdam, Swedish Museum of Natural History and University of Copenhagen in Europe; Curtin University and ANU in Australia, Osaka University in Japan; the University of Hong Kong; Beijing SHRIMP laboratory, Institute of Geology and Geophysics of Chinese Academy of Sciences, Nanjing University, and the Institute of Geology of Chinese Academy of Geological Sciences in China. The Center is planning to meet later in 2020 to discuss priorities in sample handling and analysis, as well as access to the samples for the international community.

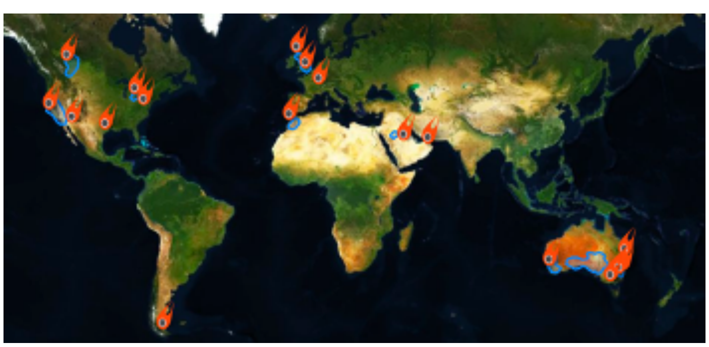


Figure 6: Map of the multi-institutional collaboration, Global Fireball Observatory, with partner networks around the world. Credit gfo.rocks website.

2.3 Mars2020 Pilbara Fieldtrip - Researching Outback Stromatolites

In 2019, the Australian Center for Astrobiology led many of the Principle Instrument Scientists of both NASA's Mars2020 and the European Space Agency's (ESA) ExoMars rover missions to the Pilbara region of Western Australia, as a training workshop in the exploration for signs of life in ancient rocks.

The fieldtrip was for one week and explored sites with claims for ancient life, where team members had the opportunity to discuss exploration strategies, sampling protocols, and arguments for and against biogenicity. A

Figure 7: Researching Outback Stromatolites. Scientists from NASA's Mars 2020 and ESA's ExoMars projects study stromatolites, the oldest confirmed fossilized lifeforms on Earth, in the Pilbara region of North West Australia. Credit NASA/JPL-Caltech.

> "The fieldtrip was conceived by NASA's Mars2020 Program Scientist, Dr. Mitch Schulte, and led by ACA Director, Prof. Martin Van Kranendonk. It was attended by 20 participants that included – in addition to the Instrument Scientists - the Director of NASA's Mars Exploration Program (Jim Watzin), the Lead scientist for NASA's Mars Exploration Program (Dr. Michael Meyer), and the Project Scientist (Dr. Ken Farley) and Deputy Project Scientist (Dr. Ken Williford) for the Mars2020 mission."

Figure 8: Dr Lucy Forman presents at the Smithsonian as part of her Endeavour Leadership Executive Award.

priority of the fieldtrip was to emphasize the importance of context in textural analysis and sample collection, and to reflect on the small-scale variability and challenges when it comes to assessment of early life materials.

2.4 Endeavour Leadership Executive Award

Dr. Lucy Forman (Curtin SSTC), received the Endeavour Leadership Executive Award. She taught electron backscatter diffraction (EBSD) to the Smithsonian Institution and the Carnegie Institute for Science, learned the processes behind meteorite curation from the curator for the Antarctic meteorite collection, Dr. Cari Corrigan, and gained exposure to all meteorite types in the Smithsonian collection. Additional collaborations included: large area mapping of martian Nakhlites using EBSD (Univ. of Glasgow); Understanding new martian shergottite sample through deformation and shock analysis (Univ. of Nevada, Las Vegas); Coordinated analysis of the Allende meteorite, using oriented sample preparation (Smithsonian Institution).

2.5 Assessing Mars

Anthony Lagain (Curtin SSTC) has interacted with a wide range of international scientists over the past year, the main ones being: Misha Kreslavsky (U. of California, Santa Cruz, CA, USA), David Baratoux (French Research Institute for Sustainable Development, Toulouse, France), Sylvain Bouley (GEOPS, Paris-Sud U., France), Francois Costard (GEOPS, Paris-Sud U., France), Stephane Erard (Paris Observatory, France), Baptiste Cecconi, (Paris Observatory, France), Daniel Mege (Space Research Center, Wroclaw, Poland) and Mark Wieczorek (Observatoire de la Cote d'Azur, Nice, France). The combined work has covered a wide variety of research activity including the assessment of the past Martian cratering flux, the origin of Martian tsunamis, the recent volcanic activity on Mars and the sharing of our automatic crater database through a common web platform.

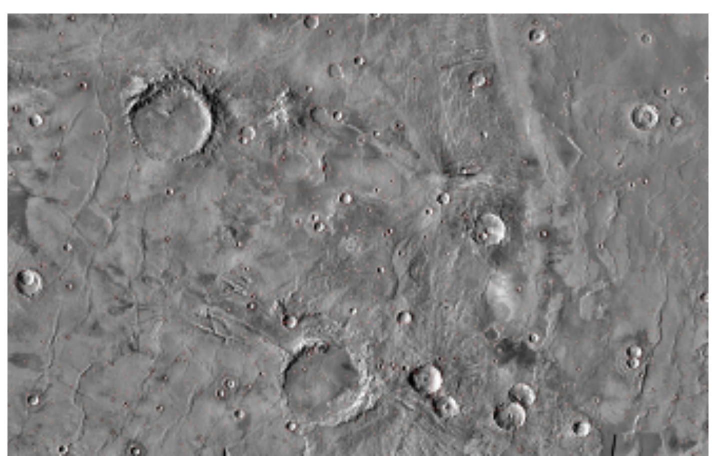


Figure 9: Surface of Mars, showing the automated crater detections in red. Curtin University

2.6 International Invited Visitors at Curtin Space Science and Technology Center

- Oded Aharonson, Weizmann Institute, Izrael
- Kai Wünnemann, Museum für Naturkunde, Berlin, Germany
- Mitch Schulte, Mars Exploration Program, NASA HQ, USA
- Mark Wieczorek, Observatoire d'Côte d'Azur, Nice, France

3. Public Engagement

The Australian Planetary Science community are high performers in Public Engagement and media participation. Our researchers and professional staff across Australia regularly appear in hundreds of events at the local and national level. They connect with thousands of families and students-- as well as professionals and politicians-- to share our research and serve as STEM role models and thought leaders in our community.

In celebrating the 50th anniversary of the historic NASA Apollo lunar landing on July 20, 1969, the Space Science and Technology Center at Curtin University produced a special exhibit for the public. Launched at the United States Consulate 4th of July Gala, the exhibition "*The Gift of Apollo*" showcased archived Apollo Mission images and quotes from researchers who were inspired by the epic achievements of exploring the Moon.

Figure 10: Prof Gretchen Benedix featured on ABC TV Asteroid Hunters.

Figure 11: The Gift of Apollo Exhibition from SSTC Curtin University, hosted by the US Consulate Perth for the 50th Anniversary of Apollo celebrations. Research Ambassador Renae Sayers stands with one of the exhibition panels.

> "The Murchison meteorite celebrated its 50th Anniversary with a major community event, attracting national media attention and guest appearances from leading Australia planetary researchers."

As part of the Mars2020 Pilbara Fieldtrip during National Science Week 2019, Prof Martin Van Kranendonk (ACA, UNSW), Dr. Mitch Schulte (NASA Mars 2020), Prof Paul Davies (Arizona State University), Renae Sayers (SSTC,

Figure 12: Prof Phil Bland, Prof Gretchen Benedix, Dr Ellie Samson, Dr Lucy Forman celebrates the 50th Anniversary of the Murchison Meteorite with public presentations and media appearances.

Figure 13: Mission Discovery 2019 cohort, Curtin University.

Curtin) and Dr. Vanessa Lickfold (BHP) appeared in "Life on Mars," a public panel sharing exploration science to the public. An ABC TV documentary was made about the field trip, the mission to Mars and the collaboration.

The Mission Discovery program is an innovative and inspirational program aiming to attract students to the science, technology, engineering and mathematics fields. Held at Curtin University over five days, hundreds of high school students worked in teams under the guidance of NASA Astronaut and ISS Commander Steve Swanson and leading researchers and mentors from the Space Science and Technology Center and Curtin STEM Outreach. Each team designed an original experiment to be carried out in microgravity conditions on the International Space Station (ISS), with the winning team's experiment to be launched and carried out in space.

Figure 14: SSTC Women in STEM, Mission Discovery Curtin University

Figure 15: Morgan Cox in the Lunar sample vault at the NASA Johnson Space Center holding a piece of the Moon.

4. Student/Early Career Participation

As the Australian Space Agency and awareness of opportunities in the space sector grow, so do the projects and PhD students who contribute to our community. This participation includes Australian students in NASA Summer Internships at LPI and Goddard (Morgan Cox and Seamus Anderson, SSTC Curtin).

Figure 16: Impact crater researchers and Earth and Mars explorers. SSTC PhD students Morgan Cox, Raiza Quintero and Andrea Rajsic with Dr. AnneMarie Pickersgill pictured in the center of the Vista Alegre impact crater located in Brazil, LMI 2019 Conference.

Figure 17: Center for Economic Development Australia Space Economy Forum, featuring (L-R) WA Chief Scientist Prof Peter Klinken, Jason Crusan VP Technology Woodside, Dr Katarina Miljkovic Curtin University, Dr Megan Clark AC Head of Australian Space Agency.

5. Mission Involvement

1. OSIRIS-REx [Phil Bland, Trevor Ireland],
2. InSight [Katarina Miljković, Elenor Samson, T Neidhart, A Rajsic.], SEIS
3. Mars Science Laboratory [Penny King]
4. Bepi Colombo [Phil Bland]
5. Hayabusa 2 [Trevor Ireland, Phil Bland]
6. Chang'e 5 [Alexander Nemchin]
7. Chang'e 6 [Alexander Nemchin]
8. Mars 2020 [David Flannery]

1. Canada 2019 Report

The Canadian Lunar Research Network (CLRN) has been a proud international node of the NASA Solar System Exploration Virtual Institute (SSERVI) and its predecessor, the NASA Lunar Science Institute, since 2008. This past year has been an exciting one in Canada for lunar science and exploration. In March 2019, the Government of Canada released its long awaited Space Strategy, which lays out the goal to "create the right conditions for the growth of the space sector, ensure that Canada's space scientists are offered a rich environment in which to pursue science excellence, fully realize the benefits of space for Canadians and leverage its ability to inspire, and ultimately help strengthen Canada's place in space." The first and most significant pillar of the Strategy is that Canada will partner on the next major human exploration and science mission; namely the US-led Lunar Gateway mission.

As outlined in the Strategy, the "Gateway will support human and robotic exploration, creating opportunities to support innovation, grow the economy, create the jobs of the future, and inspire young people to develop the skills they will need to succeed. The Gateway will be a science laboratory, a testbed for new technologies, a rendezvous location for exploration to the surface of the Moon, a control centre for operations on the Moon, and one day, a stepping stone for voyages to Mars. Canada aims to be a leading member of the next effort to push humanity into space, just as we were with the Space Shuttle program and the ISS."

This commitment to join the Lunar Gateway initiative comes with 3 major objectives; namely, through this effort, Canada will:

- Build the next-generation AI-enabled deep-space robotic system:
- Enable scientific opportunities and global partnerships;
- Guarantee the future of our astronaut program.

The second major pillar of Canada's Space Strategy is to 'inspire the next generation of Canadians to reach for the stars". As the Strategy states, space has a unique ability to inspire Canadians in the pursuit of science, discovery and technological advancement. The remaining 3 pillars of the Strategy are to "harness space to solve everyday challenges for Canadians", "position Canada's commercial space sector to help grow the economy and create the jobs of the future", and "ensure Canada's leadership in acquiring and using space-based data to support science excellence, innovation and economic growth".

With the announcement of Canada's Space Strategy, there is a critical need to strengthen and increase the size of the Canadian space community in the broad field of lunar science and exploration. The CLRN provided a report to the Canadian Space Agency that outlined how this group can help the Canadian community can meet the ambitious goals set forth by the Government of Canada.

Based on consultations with the Canadian lunar science and exploration community, the proposed revised objectives of CLRN are to:

- To strengthen and grow the lunar research (science and engineering) community in Canada;
- To build capacity in Canada by training the next generation of lunar scientists and engineers;
- To foster collaboration among Canadian academia and industry, and with international partners through SSERVI;
- To generate awareness and interest amongst the Canadian public in the Moon and about Canada's role in the Lunar Gateway and other lunar exploration initiatives;
- To highlight the industrial and other socio-economic benefits of lunar science and exploration.
- To provide expert advice to the CSA and the Canadian government on all matters related to the exploration of the Moon.

Several diverse examples of ongoing CLRN research are highlighted below.

1.1 CanMoon Analogue Mission

The CanMoon lunar sample return analogue mission was funded by the Canadian Space Agency (CSA) as part of its Lunar Exploration Analogue Deployment (LEAD) through a contract and grants to the University of Western Ontario (Western) and the University of Winnipeg. It was conducted over 2 weeks in August 2019 on the volcanic island of Lanzarote, Spain, in the Canary Islands. Lanzarote hosts several geologically young lava flows that date to as recently as the 1700's. Two field sites were used: "Janubio" in week 1 and "Nuevo Ortiz" in week 2. CanMoon was designed to accurately simulate near real-time communication between an Earth-based mission control station and a scientific rover platform operating on the lunar surface. The scientific objectives of CanMoon were:

1. Determine the geochemical and lithological diversity of rocks in the landing site region;
2. Identify and collect the best samples for radiometric age dating;
3. Identify and collect the most volatile-rich rocks;
4. Explore for crustal and mantle xenoliths in the landing site region.

The operations objectives of CanMoon were to:

1. Compare the accuracy of selecting lunar samples remotely from mission control versus a traditional human field party;
2. Test the efficiency of remote science operations including the use of pre-planned strategic traverses;
3. Evaluate the utility of real-time automated data analysis approaches for lunar missions;
4. Explore the mission control operations structure for 24/7 lunar science operations;
5. Test how Virtual Reality (VR) technology can be used to help with enhancing the situational awareness in mission control.

The results can be found in a series of abstracts in the poster session "CanMoon 2019: Lunar Sample Return Analogue Mission" at the 51st Lunar and Planetary Science Conference. Recommendations include the need for dynamic collaboration between science and planning teams, the benefit of walkabout traverse strategies, the advantages of stand-off versus contact instruments, the application of autonomous geological targeting, and the benefit of VR technology for enhancing the situational awareness in mission control. For human missions, recommendations include the value of robotic precursor missions in providing an enhanced awareness of the landing site region, the need for the development of digital field geology applications, and the value of a systematic approach to field geology training for astronauts.

Analogue missions represent integrated, interdisciplinary field campaigns conducted in terrestrial analogue environments and provide a critical pathway in preparing to return to the Moon. CanMoon provided a unique training opportunity in mission oprtations to over 60 undergraduate and graduate students and postdoctoral fellows from across Canada.

1.2 Sample Studies

Several CLRN members have been working on lunar samples, both meteorites and Apollo samples.

Dr. Erin Walton and her undergraduate student, Tatiana Mijajlovic (formerly Kopchuck), at MacEwan University have been working on a project describing shock effects in lunar meteorite NWA 032. At Western, PhD Candidate Hill, working with Drs. Osinski and Banerjee, published a paper describing the petrography and geochemistry of lunar meteorites Dhofar 1673, 1983, and 1984. This research looks at these three feldspathic regolith breccias and examined the potential of the meteorites being paired. More information on this research can be found in the published work: Hill P. J. A., Osinski G. R., Banerjee N. R., Korotev R. L., Nasir S. J., and Herd C. D. K. 2019. Petrography and geochemistry of lunar meteorites Dhofar 1673, 1983, and 1984. Meteoritics & Planetary Science 54:300–320.

Additionally, Osinski and Hill have begun working on image analysis of impactites within the Apollo collection. By analyzing the morphology and geometry of the impact melt rock within fragmental breccias and comparing it to terrestrial analogues, they aim to provide insight into the formation of these impactites. Through this semi-automatic image classification technique, the clasts of impact melt rock can be isolated and quantified through several geometric parameters. In doing so they look to provide insight into the petrogenesis of this lunar material and implication for the formation of terrestrial breccias containing impact melt rock. After primarily results, the team looks to expand the current number of samples to include a range of breccia types and begin to take the first steps in unifying the nomenclature and terminology used within the impact cratering community with lunar community. As we return the Moon common language will be essential in order for the return of high-value science targets.

1.3 Remote Sensing Studies

At Western, PhD Candidate Gavin Tolometti (co-supervised by Drs. Catherine Neish and Gordon Osinski) have been studying the surface roughness of lava flows from Craters of the Moon National Monument and Preserve in Idaho and the 2014–15 Holuhraun lava flow-field in Iceland using field observations and synthetic aperture radar (SAR). The goal of this work is to improve how scientists can interpret radar data for studying the surface roughness of lava flows on the Moon and Mars. Surface roughness tells us about the emplacement processes and style of volcanism on planetary bodies, which can provide insight into the thermophysical processes and structure of planetary interiors.

Dr. Osinski and various co-workers published a paper on transitional impact craters on the Moon. This worked used a variety of data from the Lunar Reconnaissance Orbiter spacecraft to investigate the morphology and morphometry of this class of craters on the Moon. They found clear differences in depth, diameter, and between craters in mare versus highland terrains. These differences were explained as being due to the presence of layering in mare targets, which provides pre-existing planes of weakness that facilitate crater collapse. More information on this research can be found in the published work: Osinski G. R., Silber E. A., Clayton J., Grieve R. A. F., Hansen K., Johnson C. L., Kalynn J., Tornabene L. L. 2019. Transitional impact craters on the Moon: Insight into the effect of target lithology on the impact cratering process. Meteoritics & Planetary Science 54:573–591.

1.4 Biological Life Support

The Controlled Environment Systems Research Facility (CESRF) led by Dr. Mike Dixon at the University of Guelph has signed a MOU with Moon Express for the purposes of pursuing lunar research and technology development in the field of biological life support. In a phased approach and in collaboration with Alpha Space (Houston, TX) we plan to launch a series of missions using barley seeds as the biological payload. The first phase will send barley to the ISS for deployment on the MISSE platform to assess effects on seed germination of space exposure compared to seeds inside the ISS. The environment data from this mission will inform the next phase in which a data acquisition package will be sent to lunar orbit to assess the environmental challenge of maintaining a plant growth environment (with or without actual seeds in the payload). Finally, seeds will be launched to the lunar surface where once again the technical challenge of sustaining plant growth conditions (T, VPD, radiation, CO2) will be assessed with the possibility of also germinating a sample of barley seeds if possible. This phased program represents necessary incremental advances in taking plants to the moon and developing the capability of eventually successfully supporting plant growth in the context of the field of biological life support.

1.5 Space Health

The Space MRI Team led by Dr. Gordon Sarty at the University of Saskatchewan has completed three paper studies to date for the CSA giving conceptual designs for wrist- and ankle-size Magnetic Resonance Imagers (MRIs) for the International Space Station (ISS) and for a comprehensive medical imaging system for future deep-space transports. Over the past half-decade thery have built two wrist-size prototypes (named the “Sparrow” and “Owl” MRIs), which are now both being retrofitted. The Owl MRI is being used to work out the final bugs in the design of an ankle-size MRI (the “Merlin” MRI) that will be tested in zero-g on NRC’s Falcon 20 jet. The main MRI technology being developed is called “TRASE” and was invented at the NRC Institute for Biodagnostics. Looking to the future they have also started to develop a newer MRI technology based on diamonds with nitrogen vacancies and we are using the Sparrow MRI to understand the basic physics behind the new technology. Their ultimate objective is to build MRIs for use on the Moon where they will be used for both clinical diagnostics and to gain a basic understanding of how the human body responds to short- and long-term exposure to lunar gravity and the lunar radiation and dust environment. A natural first demonstration and use of the MRI technology to that end would be with a wrist-size MRI on the first piloted Artemis lunar landers.

At Health Canada a group of scientists is continuing their biodosimetry program with CSA to assess the chromosome damage in astronauts while on the ISS. This can be used as an estimate of the dose received by the astronauts. They are in the process of renewing an MOU with the CSA for the next five years. Due to the lack of Canadian astronauts travelling to the ISS, the MOU will incorporate research that will strengthen the biodosimetry program through examination of other endpoints, modelling of radiation quality and the development of adverse outcome pathways (in collaboration with NASA) for exposure to space radiation leading to health outcomes. This process will help understand the biological mechanisms leading to the health outcomes and identify gaps in knowledge for future research.

2. Inter-team/International Collaborations

Dr. Catherine Neish was a collaborator on the NASA SSERVI FINESSE team from 2014-19. She held a CSA FAST award from 2015-18 to collaborate with the FINESSE team, along with Dr. Claire Samson at Carleton University, Dr. Raymond Francis at JPL, and Dr. Antero Kukko of the National Land Survey of Finland.

Dr. Osinski was also part of the NASA SSERVI FINESSE team and is part of the new Remote, In Situ, and Synchrotron Studies for Science and Exploration 2 (RISE2) and Resource Exploration and Science of OUR Cosmic Environment (RESOURCE) teams.

Dr. peter Brown (Western) is part of the Center for Lunar and Asteroid Surface Science (CLASS) team.

Health Canada (HC) has been providing biodosimetry analysis for Canadian and European Astronauts since 2007 through coordination with the CSA. Over this time, data has been accumulated for ten astronauts who have who have completed long-duration missions to the International Space Station (ISS).

Dr. Cloutis of the University of Winnipeg has been involved in several international collaboration efforts. Recently Dr. Cloutis has worked as the Science Principle Investigator for the Japan Aerospace Exploration Agency (JAXA) Selene-2 mission. While this mission has been canceled, components of the former orbiter, lander, and rover mission may likely be incorporated into new future international collaborations. Dr. Cloutis has also worked with the Chinese National Space Administration (CNSA) as a collaborator on the Chang’e 3 mission. Dr. Cloutis lent his expertise to the analysis and interpretation of spectroscopic data collected on the lunar surface by the Chang’e 3 lander and Yutu rover. Additionally, Dr. Cloutis has been involved in a joint Canadian Space Agency (CSA) / European Space Agency (ESA) effort to develop a 12U cubesat for use in volatile detection in permanently shadowed regions of the lunar surface.

Mission Control works with several academic and industry collaborators to advance its portfolio of onboard robotics and mission operations software technologies. In the United States, Mission Control's primary working relationship is with Dr. Ryan Ewing at Texas A&M University. Dr. Ewing is the PI for a Mars analog operations study funded by NASA PSTAR that leverages Mission Control's robotics and operations software and expertise in planning and orchestrating complex analog field trials. Called SAND-E (Semi-Autonomous Navigation for Detrital Environments). As part of this project, Mission Control collaborates with Co-Is from NASA JSC, Stanford University, Purdue University, Harvard University, MIT, and Reykjavik University.

3. Public Engagement

Dr. Mike Dixon continues to support the Tomatosphere project now in its 20th year and over 4 million students engaged and counting. His group is integrating their "barley on the Moon" aspirations with their outreach legacy represented by Tomatosphere.

The Space MRI Team's PI Gordon E. Sarty has given several radio and print media interviews over the past half-decade in addition to public talks at monthly meetings of the Royal Astronomical Society of Canada. Last year a presentation titled "Canada is Going to the Moon: And MRI from Saskatchewan will be there!" was given to grade 6,7,8 students at a "Let's Talk Science" event (they asked about making babies in space!). The PI was proud to deliver the annual Father Lucien Kemble Lecture at the Saskatchewan Summer Star Party in Cypress Hill last summer with a talk titled "MRIs for Moon Bases."

Mission Control has a proven track record of executing effective and far-reaching education and public outreach activities related to space exploration, science and autonomous systems. Over the last five years students on four continents have operated a planetary rover prototype deployed at analog sites around the world as part of their Mission Control Academy immersive, technology-based educational experience. Mission Control Academy is a simulated rover mission that challenges participants to design and operate a planetary exploration mission, culminating in an opportunity to remotely drive a real rover prototype in a Mars-like environment.

At Western, the newly formed Institute for Earth and Space Exploration expanded on the work of its predecessor, the Centre for Planetary Science and Exploration (CPSX), in running an active public education and engagement program. A series of events and activities were held around the 50th anniversary of the Apollo 11 Moon landing. Moon-focused content was integrated into their Space Explorers summer camp program and Space Academy program, for children in grades 4 to 8. Dr. Osinski received funding from the Canadian Geological Foundation for the "Moon Rocks!" initiative, which developed classroom workshops, rock kits comprising Moon analogue rocks, and an Exploring the Moon in Minecraft activity. Their annual International Observe the Moon Night event in Fall 2019 was also a huge success.

4. Student/Early Career Participation

A number of undergraduate and graduate students have participated in CLRN activities over the past year. Notable examples of promotion, retention, and movement, include Dr. Michael Zanetti – who was a postdoctoral fellow with Drs. Neish and Osinski at Western and who has moved on to a new position as a civil servant at NASA Marshall Space Flight Centre – and Dr. Patrick Hill – who completed his PhD at Western and moved on to a postdoctoral position at the University of Alberta with CLRN faculty member Dr. Chris Herd.

5. Mission Involvement

1. Lunar Reconnaissance Orbiter, Dr. Catherine Neish, Mini-RF, Co-investigator
2. Lunar Reconnaissance Orbiter, Dr. Ed Cloutis, Lunar Reconnaissance Orbiter Camera, Co-investigator
3. Super-SWEPT, Name, Instrument/experiment, Role
4. SWEPT-2, Name, Instrument/experiment, Role
5. VMMO lunar 12u Cubesat, Dr. Roman V Kruzelecky, Co-investigator
6. VMMO lunar 12u Cubesat, Dr. Ed Cloutis, Co-investigator
7. Selene-2 (JAXA), Dr. Ed Cloutis, Co-investigator
8. Chang'e 3, Dr. Ed Cloutis, Collaborator
9. HERACLES (Mission Concept), Dr. Gordon Osinski, Chair, international Science Definition Team (iSDT) Site Selection and Science Scenario Group.

1. Italy 2019 Report

Italian scientific community has a long, storied partnership with SSERVI, starting with the establishment of the Italian Node at INFN Laboratori Nazionali di Frascati, but more recently, with the Italian Space Agency joining as an Associate partner, coordinating the initiatives of the domestic research centers and Universities. Italy's national scientific community has participated in several international initiatives for lunar and asteroid exploration, both in multilateral and bilateral cooperation. A good opportunity to present and discuss results and perspectives in the field will be the "8th European Lunar Symposium" that will be hosted in Padua, Italy, on 12th-14th May 2020.

1.1 INFN-LNF

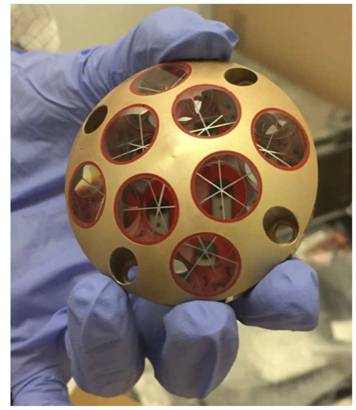
The SCF_Lab of INFN-LNF works jointly with the Matera Laser Ranging Observatory (MLRO) of the Italian Space Agency-CGS (Space Geodesy Center). The most relevant achievements in 2019 follow:

- November 22, 2019, kick-off meeting of the JointLab 5-year Agreement between the national laboratories INFN-Frascati and ASI-Matera for laser retroreflectors and laser ranging in the whole solar system. This agreement does not include current Mars surface missions (ExoMars 2016/2020, InSight 2018 and Mars 2020).

- Italian nano-pico laser retroreflectors for ESA's Hera mission to the double asteroid system, Didymos. Hera was approved in November 2019 by the EU-ESA Ministerial Council for launch in 2024. Hera has a laser ranging/altimetry instrument onboard. Upon demand by ESA, the Mars 2020 flight spare micro-reflector could be also delivered to Hera.

pico and nano-reflectors
(4.7 gr 10.2 gr)

Mars micro-reflector (25 gr)



Moreover, during 2019, INFN and ASI negotiated and prepared to kick off an ESA contract for participation in a NASA mission to the lunar surface in 2022, and the delivery to ESA of a dual pointing actuator of the INFN-ASI next generation lunar laser retroreflector "MoonLIGHT." This contract also includes the delivery of one MoonLIGHT instrument to ESA.

1.2 INAF

The INAF team is deeply involved in the lunar exploration preparatory activities, especially as part of the ESA PROSPECT user group. The Italian science team is composed of a wide group of scientists involved with lunar science and exploration. The **Prospect User Group** members have been selected by ESA to define and ensure the scientific requirements of PROSPECT, to consolidate PROSPECT science objectives, to ensure PROSPECT is operated effectively at the lunar surface, and to increase the scientific return of the expected data. The main purpose of PROSPECT is to support the identification of potential resources on the Moon and to assess the utilization of those resources. Water and other volatiles found at the surface of the Moon could potentially provide major assets for future exploration and represent vital consumables for human explorers which could also be a source of oxygen for life support systems. Moreover, hydrogen and oxygen can be extracted from lunar soil and used as fuel. Some members of the INAF Team are part of the ESA Lunar Science Team that is in charge of preparing a plan that would be used as the basis for scientific investigations and payloads for ESA's future lunar exploration activities. This is intended to begin with the selection of a pool of payloads for potential flights in the 2020-2025 timeframe. The intention is that this plan will define the European science community's priorities for lunar exploration that can be addressed by missions to the lunar surface in the coming years.

Moreover, some INAF researchers participate on the International Lunar Research Team, coordinated by ESA and CNSA. The goals of this research team are the cooperation between European and Chinese scientific teams to support the missions of both agencies, enhance the overall scientific return, and to prepare for an international lunar research station.

INAF scientists are also strongly involved in the field of Astrobiology, being active members of the just established "European Astrobiology Institute (EAI)," created in 2019. This consortium of European researchers, higher education institutions and organizations, as well as other stakeholders, carries out research, training, outreach and dissemination activities in astrobiology in a comprehensive and coordinated manner to secure a leading role for European Research in the field.

The European Astrobiology Institute aspires to become a primary forum for the development of European Astrobiology ensuring that this relatively new interdisciplinary research field is established across Europe.

Key research areas are: Formation and Evolution of Planetary Systems and Detection of Habitable Worlds, Planetary Environments and Habitability, Evolution and Traces of Early life and life under extreme conditions, Biosignatures and the Detection of Life beyond Earth. The associated fundamental research questions require a concerted effort by scientists from different fields.

1.3 Politecnico di Milano

Politecnico di Milano is carrying out activities related to **In Situ Resources Utilization ISRU** plant design and prototyping to extract water from Moon regolith. In particular, activities are focused on the Carbothermal Reduction (CRB) process, solid-gas based, using methane containing the endothermic reaction temperatures in the range of 950-1000°C. The plant has been assembled, functional tests run already; the plant, assembled in PoliMi, is going to be switched on for the CRB process yield verification begin of March 2020. Activities are carried on in synergy with ESA, ASI, and OHB company.

A correlated set of activities is related to **Lunar South Pole soil simulant characterization** in thermal vacuum conditions. In fact, reproducing a planetary soil simulant bed is a tough challenge starting from the need of repeatable procedures to prepare the soil with desired physical properties, to the need to ensure its preservation during thermal-vacuum operations. Politecnico di Milano is also part of the PROSPECT user group of ESA, responsible for science operations of the PROSEED - DRILL tool. Particular attention is given to modelling and verifying the thermal energy exchange process between the icy soil - sampled at lunar pole – and the drilling tool to avoid any sublimation of the icy content that scientists are interested in.

In the area of ISRU for planetary manned missions, PoliMi-ASTRA is carrying on applied research **in biomass growing in space** for CO2 recycling and biomass production. The aim is to finalize a small prototype to be sent on board one of the incoming lunar landers, for in-situ verification.

Politecnico di Milano, ASTRA Team, is also working on **Vision based navigation and Hazard avoidance for Autonomous landing and proximity maneuvering;** in particular, the team is currently involved in the AIVIONICS ESA study to assess the effectiveness of Artificial Intelligence techniques in GNC image processing for Vision Based Navigation of a swarm of autonomous spacecraft; a strong verification campaign with HIL is included in the study, exploiting the in-house GNC experimental laboratory equipped for lunar landing and for proximity maneuvering, the two scenarios considered in the study.

PoliMi-ASTRA is developing 2 PhDs in collaboration with ESA Mission analysis division, on the Mission analysis and mission operations from systems located in the Cis-lunar environment, orbiting on non-keplerian orbits like the NRHOs are. The first is related to the LOP-G scenario and is focused on stability families and on the design and definition of rendezvous and proximity maneuvering; the second assesses the capability of long-duration missions in the cis-lunar environment in reacting to a potentially

Carbothermal reduction plant demonstrator @PoliMi

hazardous object on a collision trajectory with Earth.

The PoliMi Team is deeply involved in **small bodies related research**, too. In particular, broadly speaking 3 areas can be identified: bodies gravitational models for non-uniform mass distribution; slow and hyper velocity particles trajectory short\long time evolution; proximity maneuvering for scientific requirements satisfaction, trajectory definition, and GNC design to maximize the scientific return. PoliMi-ASTRA has been involved in AIM-ESA mission phase A to define trajectories and operations to both get to the didymos binary and move in a multi-regime gravitational environment; it is currently involved in advanced vision-based navigation for relative dynamics reconstruction for the HERA-ESA mission, in the LICIA cubesat mission (ASI financed), and for the cubesat trajectory with GNC and attitude control from release to end of life.

1.4 International Research School of Planetary Sciences

The International Research School of Planetary Sciences is a non-profit organization devoted to research and post-graduate education. The School is an emanation of the Universita' d'Annunzio and hosted by Dipartimento di Ingegneria e Geologia (InGeo). Planetary research mainly deals with the sub-disciplines of geology, geochemistry, geophysics, petrology, and exobiology. However, the

The testing of SherpaTT

IRSPS is not limited to these subjects and it welcomes scientific contributions from any field of planetology. Also, the educational programs are not restricted to those fields and they will cover the entire spectrum of planetary disciplines by joint ventures and collaborations with other international institutions. IRSPS is working for ESA/Thales Alenia Space-Italia on the analysis of the landing sites engineering constraints for the ExoMars missions. The analysis includes the assessment of the physical and geological characteristics of the areas, the evaluation of the risk and the definition of the Hazard in geographical terms. IRSPS conducts tests jointly with the Faculté de Sciences of the Université Cadi Ayyad (Marrakech Morocco) at the Ibn Battuta Centre (Morocco) for exploration and field activities on Mars and Lunar analogues. Following the tests conducted for the ExoMars radar altimetry and DREAMS instrument, an analogue test campaign was devoted to testing the Sherpa TT, DFKI 2nd generation rover for Mars exploration, developed under a European Union contract.

With expertise in characterizing planetary analogues for instrument and technology testing and operations, the IRSPS team joined the NASA/SSERVI Analogs Focus Group, participating in group teleconferences and contributing to the virtual seminars series.

2. Public Engagement

In celebrating the 50th anniversary of the Apollo XI landing on the Moon, the Museo Civico di Rovereto arranged the "La Luna, e poi?" exhibit with sponsorship from the Italian Space Agency and important support from NASA

SSERVI. The exhibit was visited by about 20,000 persons between December 8th 2018 and August 25th 2019, and was enriched by several side events and initiatives. Together with the illustrated panels, audio/video and the exhibited models and pieces of hardware from space missions, the visitors also enjoyed outreach events, themed conferences, observation nights, guided tours, in addition to many workshops for children and schools -- and through the use of tools such as Moon Trek, which proved to be very useful for teachers and students. After August, the exhibit was transferred to Genoa and Verona for their respective local science festivals, with several additional requests to host it.

3. Mission Involvement

The Italian Space Agency has an important heritage in the development of instruments for Solar System Exploration missions, often in cooperation with international partners.

Exhibition

Exposed moonrock sample

In the past years, ASI also recognized the potentiality of small satellites in the class of nanosatellite/cubesat, as alternative means to implement space missions in a fast, cheap and effective way.

"Argomoon" is a 6U cubesat selected in 2016 by NASA HQ Exploration Systems Mission Directorate (ESMD) as a Secondary Payload for the Artemis 1 mission of the Space Launch System (SLS)-- the heavy-lift launch vehicle designed for space exploration beyond Low-Earth Orbit. The first part of the ArgoMoon mission will take significant photographs of the launcher, and in the following six months, the satellite will orbit around the Earth with an apogee close to lunar orbit, to collect pictures of the lunar surface for science and outreach purposes. The ProtoFlight Model is almost complete and will undergo the final qualification/acceptance test campaign before being shipped to the USA for final testing and integration onto the launcher.

NASA again selected a similar platform, named **"LICIACube - Light Italian Cubesat for Imaging of Asteroids,"** to witness the impact effects of the NASA's Double Asteroid Redirection Test (DART) on the secondary asteroid of the binary system Didymos, in order to test orbit deflection methods for Planetary Defense purposes. The LICIACube will launch piggyback on other DART spacecraft but will then separate in proximity of the target to perform an autonomous fly-by of the binary Didymos system during the final part of the DART mission, collecting pictures of the asteroid surface and of the generated ejecta plume. During 2019, the APL – DART team review was completed, and CDR successfully concluded.

Both missions will allow the Italian community to setup and validate complete end-to-end space systems operating in the deep space environment, paving the way for future opportunities for cooperation and national initiatives.

As Italian initiative currently supported by ESA, the **Lunar Meteoroid Impacts Observer (LUMIO)** is one of the four projects selected within ESA's SysNova Competition No. 4 "Lunar CubeSats for Exploration" (LUCE). The goal of the competition was to perform multiple Phase 0 studies for nanosatellites (CubeSats) to conduct scientific and technology demonstrations when deployed by a mother ship around the Moon. LUMIO is a mission to observe, quantify, and characterize meteoroid impacts by detecting the impact flashes on the lunar far-side. This will complement the knowledge gathered by Earth-based observations of the lunar nearside, and provide global information on the lunar meteoroid environment.

LUMIO was awarded co-winner of the LUCE competition, and as such it was later assessed by a team of ESA experts in a series of dedicated sessions at the Concurrent Design Facility (CDF) at ESTEC. Politecnico di Milano has been Prime Contractor and principal investigator of the Phase 0 study for LUMIO. The Phase A activity is anticipated to start in February 2020 under ESA contract with ASI funding.

REFERENCES:

1. Porcelli, L., Tibuzzi, M., Mondaini, C., Salvatori, L., Muccino, M., Petrassi, M., ... & Bianco, G. (2019). Optical-Performance Testing of the Laser RetroReflector for InSight. Space Science Reviews, 215(1), 1.

2. Formisano, M., De Sanctis, M. C., De Angelis, S., Carpenter, J. D., & Sefton-Nash, E. (2019). PROSPECTING the Moon: Numerical simulations of temperature and sublimation rate of a cylindric sample. Planetary and Space Science, 169, 8-14.

3. Dell'Agnello, S., Delle Monache, G. O., Porcelli, L., Tibuzzi, M., Salvatori, L., Mondaini, C., ... & Bianco, G. (2019, March). Laser Retroreflectors for InSight and an International Mars Geophysical Network (MGN). In *Lunar and Planetary Science Conference* (Vol. 50).

4. Geppert, W., Brucato, J. R., Cabezas, P., Falanga, M., Gargaud, M., Henning, T., ... & Martínez-Frías, J. (2019, June). The European Astrobiology Institute–a new pan-European initiative in the field. In 2019 Astrobiology Science Conference. AGU.

5. Zanotti, G., Lavagna, M., & Capannolo, C. (2019, January). Assessment on small bodies impacts and fragments plume dynamics modelling through SPH with LS-DYNA solver. In Geophysical Research Abstracts (Vol. 21).

6. Capannolo, A., Ferrari, F., & Lavagna, M. (2019). Families of Bounded Orbits near Binary Asteroid 65803 Didymos. Journal of Guidance, Control, and Dynamics, 42(1), 189-198.

7. Bucci, L., & Lavagna, M. (2019). Sun-Earth Libration Points Transfers Through Earth-Moon Gravity Assist. In 70th International Astronautical Congress (IAC 2019) (pp. 1-7).

8. V. Di Tana, B. Cotugno, S. Simonetti, G. Mascetti, E. Scorzafava and S. Pirrotta, "ArgoMoon: There is a Nano-Eyewitness on the SLS," in IEEE Aerospace and Electronic Systems Magazine, vol. 34, no. 4, pp. 30-36, 1 April 2019.

9. Gai, I., Zannoni, M., Modenini, D., Tortora, P., Pirrotta, S., & Tana, V. D. (2019, January). Orbit Determination of LICIACube: Expected Performance and Attainable Accuracy. In Geophysical Research Abstracts (Vol. 21).

10. P. Tortora and V. Di Tana, "LICIACube, the Italian Witness of DART Impact on Didymos," 2019 IEEE 5th International Workshop on Metrology for AeroSpace (MetroAeroSpace), Torino, Italy, 2019, pp. 314-317.

11. A.Capannolo, G.Zanotti, M.Lavagna, E. Mazzotta Epifani, V. Della Corte, M.Zannoni, I.Gai,S.Pirrotta, M.Amoroso, Challenges in LICIA Cubesat trajectory design to support DART mission science, 70th International Astronautical Congress, Washington, 2019

12. Speretta S. et al. (2019) LUMIO: An Autonomous CubeSat for Lunar Exploration. In: Pasquier H., Cruzen C., Schmidhuber M., Lee Y. (eds) Space Operations: Inspiring Humankind's Future. Springer, Cham

1. Japan 2019 Report

Masaki Fujimoto, Deputy Director General, ISAS/JAXA

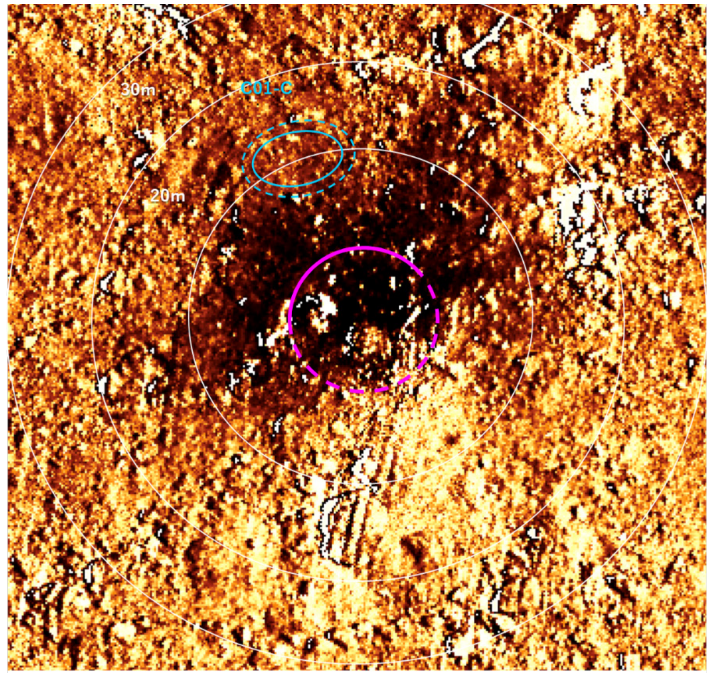
While it has been a SSERVI affiliate for some time, JAXA officially became an Associate Member of SSERVI in July 2019. Here are the highlights of the SSERVI-related activities deployed by JAXA.

1.1 Small Body Exploration

Hayabusa2 is an asteroid sample return mission to the C-type asteroid Ryugu. The top science goal is to understand the water delivery process to our planet (Earth would have stayed too dry to develop its habitability if it were not for this process).

After its arrival at Ryugu in June 2018, Hayabusa2 made various remote sensing observations that have been highlighted in several publications. The material characteristics inferred from remote sensing data implies that Ryugu surface materials are not similar to any meteoritic samples analyzed so far, elevating expectations for the samples to be returned by Hayabusa. This implication was reinforced by observations on the surface by the small robots of MINERVA-II (Japan) and MASCOT (Germany/France).

While we had expected to find a reasonably large flat area to touch-down, the first shocking information brought by remote sensing observations was the fact that rough features blanket most of the surface of Ryugu. The first touch-down and sampling (TD1) was delayed from October 2018 to February 2019, after a dedicated struggle to find a small flat spot in which sampling could be done safely, and technical studies to develop a safe sampling scheme from a spot that was much smaller than what had been assumed prior to launch. Ultimately a perfect sampling operation was performed, with highly desirable Ryugu samples stored safely in the spacecraft. TD1 was followed by an impactor experiment which created an artificial crater on the surface of Ryugu. The team debated TD2 after discovering another small flat spot in close proximity to a crater which was TD-able and covered by excavated sub-surface materials. After pushing back against the argument that the safety of the TD1 samples



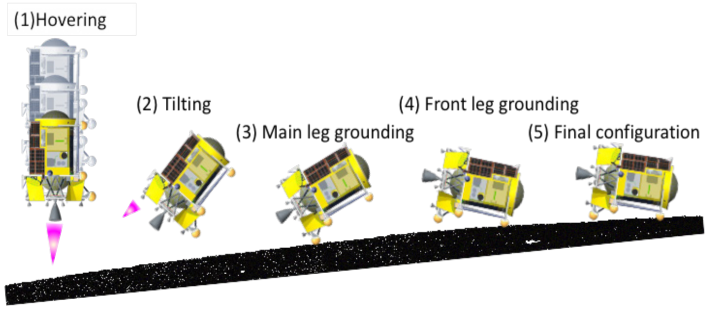
The site of TD2: crater (purple), TD site (blue) and dark materials shows the distribution of excavated sub-surface materials.

were a higher priority than the merit to be gained by a second touch-down, the team let Hayabusa2 go for TD2. With a successful TD2, sub-surface materials, which are expected to be un-weathered and fresh, were stored inside the spacecraft.

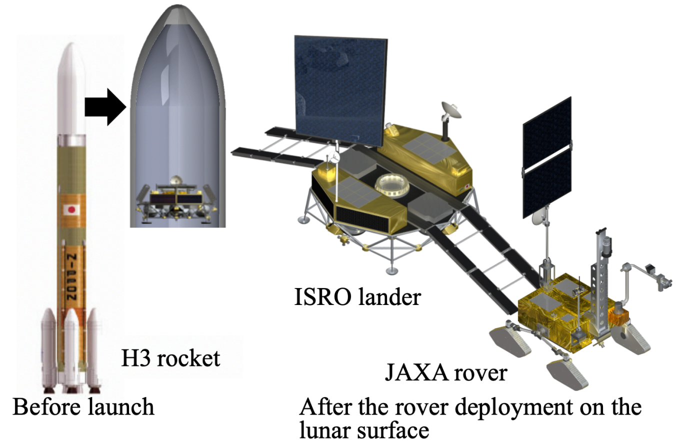
Hayabusa2 left Ryugu in November 2019 and is on its way back to Earth with the sample return capsule re-entry expected in December, 2020 (although the COVID-19 situation may force the team to modify its timing). The spacecraft itself will stay healthy in space, and there is a plan to assign it with another small body mission with a planetary defense theme.

1.2 Lunar Exploration

Smart Lander for Investigating Moon (SLIM) is a technology demonstration mission to be launched in FY2021 aimed at demonstrating precise landing technology (landing within a 100 m radius landing circle) of a small and lightweight lander (~200 kg). It will be the Japan's first lunar-landing mission. Safe landing on a relatively steep sloped area is also within the scope of the objectives (indeed, this is required from the condition of its landing target area close to Nectaris basin). This is why SLIM adopts a unique two-staged landing procedure.



The two-staged landing procedure of SLIM



Configuration of the lunar exploration mission

Olivine exposures of possible mantle origin were found by Kaguya (JAXA lunar orbiter launched in 2007) observation, but their scientific potential has been left unexplored. SLIM will precisely land in the area that shows Olivine exposures. The high-resolution Multiband Camera onboard will detail the mineralogy and image olivine-rich exposures in close proximity to the lander.

Regarding international cooperation, we are considering carrying NASA's small reflector and welcoming NASA science team members. Our strategy is to let SLIM illuminate a way for small landers to contribute to future planetary exploration.

Once the precise landing technology is demonstrated, JAXA plans to apply it for enabling its **lunar polar exploration mission**. The precise landing technology is indispensable for polar missions (and for more demanding future landing missions) because the targeted landing sites that have been identified to achieve key science goals are likely to be very small and may be situated next to potentially hazardous areas.

Currently, the abundance, condensation mechanism, and lateral and vertical distribution of water in the lunar polar region is unclear. JAXA's lunar polar exploration mission, to be developed in collaboration with ISRO, will address these issues. Further international collaboration with NASA and ESA are under consideration. The goal, beyond gaining knowledge of the lunar polar water, is to evaluate the possibility for utilizing water as a resource for future missions.

The lander will be situated in the polar region (> 85 degree in latitude) and a rover will be deployed to investigate water quantity (how much), water quality (does it contain other phases such as CO2 and CH4 or not) and water usability (how deep do we need to drill or how much energy is required for drilling the regolith to derive the water). The mission is in Phase A now, after passing the definition review and project readiness review by JAXA in 2019.

The launch will be by a Japanese H-III rocket around 2023. The plan is that ISRO and JAXA will develop a lander and a rover, respectively (precise landing technology will be provided by JAXA). The mass of the rover is around 350 kg, including the payload with multiple instruments designed for the investigation described above. The rover is capable of drilling to 1.5m deep and can transfer regolith samples from that depth to the instruments onboard. The rover is also designed to function inside a shadowed area for a short period of time; overall mission duration after the rover deployment is more than two months. Data analysis conducted by the JAXA Lunar and Planetary Exploration Data Analysis Group (JLPEDA) of both Kaguya and Lunar Reconnaissance Orbiter data established the basis for selecting candidate landing sites. There are at least several attractive candidate landing sites, which implies that coordination among multiple polar missions planned by different agencies (including VIPER) is anticipated.

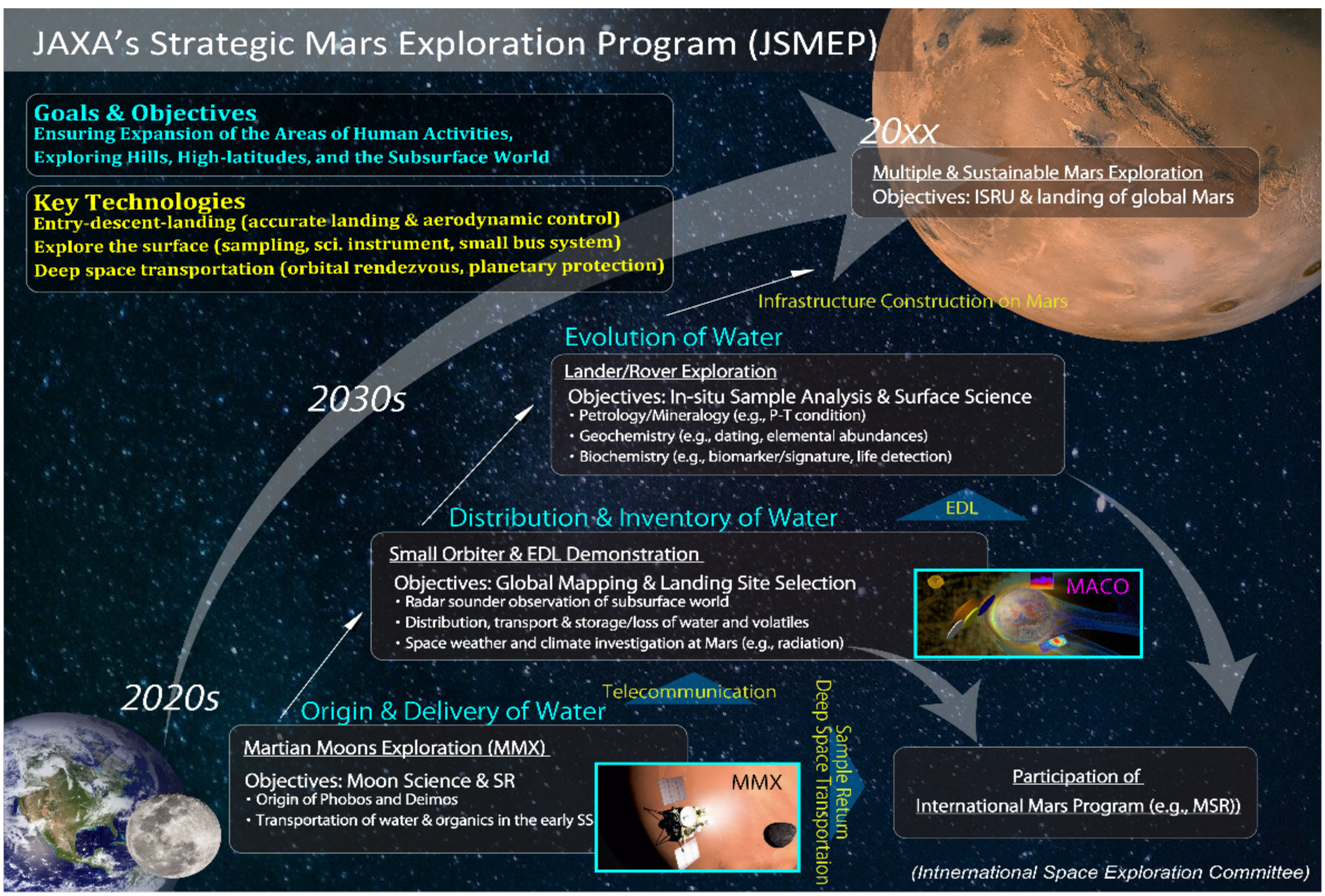
Gateway can provide an environment with stronger vacuum, stronger cosmic rays, and stronger UV light compared with the International Space Station (ISS). In microgravity and space life science experiments in low Earth orbit in the past, such as those on the Space Shuttle and the ISS, the relevant Japanese research community has continued to produce results that have attracted international attention. With this foundation, the Japanese science and exploration communities will continue contributing to worldwide research endeavors on Gateway. Indeed there are advantages that Gateway possesses: (1) lower influence by the Earth environment (atmosphere, ionosphere, magnetosphere), (2) the possibility of long baseline observations in coordination with ground-based facilities, (3) opportunities for expanding the scope of experiments performed on ISS, (4) a step toward a lunar surface observatory and (5) continuous long-term observations.

A survey of ideas from Japanese researchers and industries, identified the following benefits of Gateway:

- Constructing such a base would enable new observations and experiments that make use of the unique environment relatively unaffected by the cislunar and Earth environments
- Using both the ISS and Gateway--and the unique gravity, cosmic ray, and solar environments there--could help inform future experiments on the lunar surface
- Collaboration between the scientific community, private companies, and other partners, could foster research needed for future human exploration of Mars
- Provides benefits to human society through scientific achievements made possible by collaboration between scientists in space science and a wide range of other fields

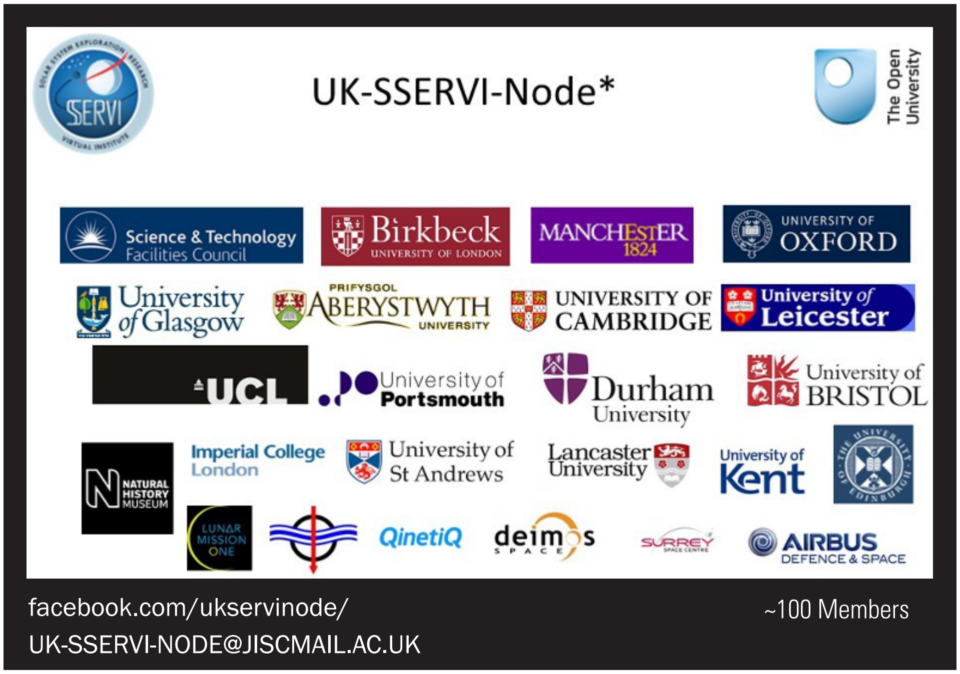
1.3 Mars Exploration

JAXA is determined to stay on the front lines of small body exploration. Following Hayabusa2, JAXA is preparing **Martian Moons eXploration (MMX)**, with a similar science theme (water delivery in the early solar system history). MMX is a Phobos sample return mission to be launched in 2024. JAXA's visibility in small body exploration is high enough to unite several international partners, each contributing significantly for MMX. From the U.S., NASA supports provision of a gamma-

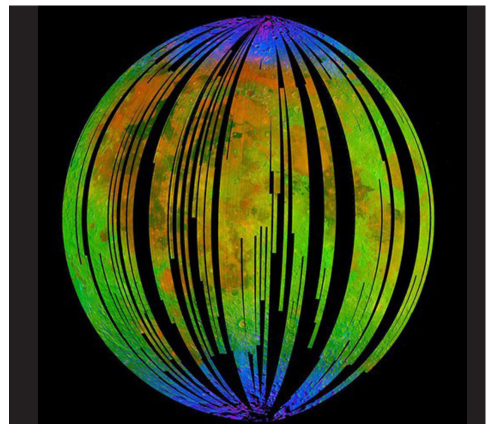


ray neutron spectrometer (MEGANE from APL) and a pneumatic sampler (P-sampler from HBR, in addition to a coring sampling system (C-sampler) by JAXA), and various other activities necessary for the mission. A rover is being developed by CNES and DLR, who partnered with JAXA in Hayabusa2 as well. Development of landing gears and sampling systems has proceeded effectively because of Phobos simulants prepared and delivered by the SSERVI network. We should note that support from SSERVI, which first emerged before JAXA became an official member, has been critical in the timely development and testing of MMX sampling systems.While MMX is clearly a small body sample return mission, we at JAXA regard it as a key element in JAXA's Moon-to-Mars program. This notion has been enhanced when we estimated the amount of Mars materials implanted in the surface of Phobos to be much larger than previously estimated. When we prepared JAXA's argument for MMX mission categorization by COSPAR Planetary Protection Panel, the question of how much debris from crater-forming events on Mars is sitting on the surface of Phobos was revisited. Debris from the Martian surface, ejected from Mars, has subsequently accumulated on Phobos. The Martian samples on Phobos have been sterilized sufficiently during the transport process to put MMX in the unrestricted return category (as agreed by the Panel). The larger amount of debris indicates that MMX could have more of a Mars sample return flavor than previously imagined. Planning discussions for MMX sample analysis have begun, and setting the strategy for Martian samples is on the agenda. MMX is accelerating the Japanese community's interest in Mars exploration. The idea is highlighted in the JAXA's Strategic Mars Exploration Program (JSMEP), which will explore the untouched Mars subsurface world with a radar sounding orbiter mission in 2020's and a rover/lander exploration in 2030's. Subsurface exploration is a promising target for future human explorers, and a new science frontier in the field of aqua-planetology and astrobiology. The astrobiology community in Japan is growing and has made contributions such as uncovering the possible existence of a subsurface water (ice) world (e.g., Usui et al. 2015), which may be more favorable to extant or even present life on Mars (Suzuki et al. 2020; Koike et al. 2020) than previously thought.

1. United Kingdom 2019 Report



- Samples
- Remote sensing
- ISRU
- Instrumentation
- Modeling



Apollo Next Generation Sample Analysis Program

NASA announces solicitation for the Apollo Next Generation Sample Analysis Program (ANGSA)

The goal of the ANGSA Program is to maximize the science derived from samples returned by the Apollo Program in preparation for future lunar missions anticipated in the 2020s and beyond. To achieve this, ANGSA solicits research on specially curated materials from the Apollo 15, 16, and 17 sample collections, which were returned to Earth in 1971-72.

The ANGSA program will consider only proposals that focus on the analysis of the following list of Apollo samples, although proposers are welcome to include other lunar samples in their studies to help understand the specially curated samples, that are defined as:

* Unopened vacuum-sealed Apollo samples
* Frozen Apollo Samples
* Apollo Samples stored in Helium

2. Public Engagement

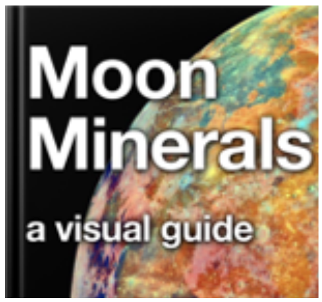
2.1 Public Talk and Tartan Presentation Ceremony

2.2 European Lunar Symposium

2.3 Open University Moon Night

Open University's Moon Night is an annual public engagement event that was held Friday, 6 December, 2019; with ~200 attendees in-person (+ >> online).

- 8-13 years old students from 5 local schools
- Release of 'Moon Minerals' iBook



2.4 Living on the Moon

A consortium with OU (lead), Manchester, Oxford, NHM, Birkbeck.

- >6k individual engagements
- Extremely positive feedback
- Multiple media coverage

The 2019 ELS had ~130 attendees, ~60 orals and ~40 posters.

Jim Green, NASA Chief Scientist, at the Tartan Presentation Ceremony.

ELS 2019 (Romain, Katie and team)

2.5 Apollo 50th celebrations

- Numerous contributions (tv, radio, print, social media)
- Lionel Wilson (Lancaster); Katie Joy (University of Manchester); Ian Crawford (Birkbeck College University of London; Mahesh Anand (The Open University)

2.6 Open Learn

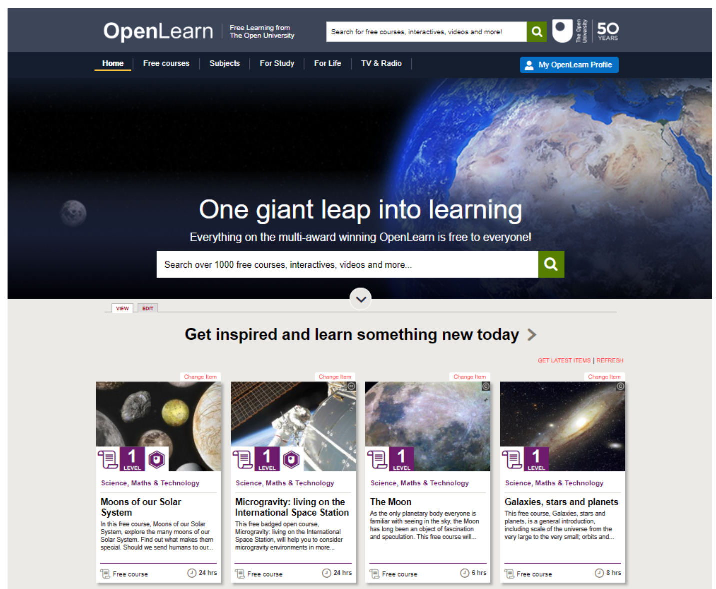
- Free Open Educational Resources
- Several Moon-related articles released on the occasion of 50th anniversary of Apollo 11

2.7 Eight Days

8 Days was a BBC Drama-Documentary Co-produced by OU-BBC with Mahesh Anand serving as Academic Adviser.

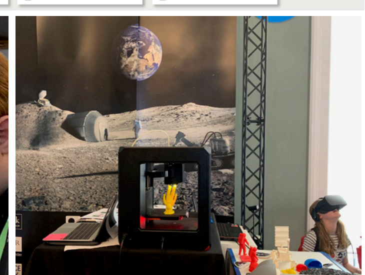
2.8 RAS Specialist Discussion Meeting

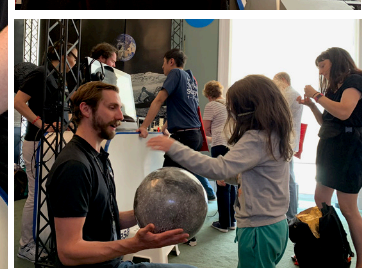
The RAS Specialist Discussion Meeting was held Friday, 11 Oct., 2019. It was organized by Mahesh Anand, Katie Joy, and Lydia Hallis.



3. Mission Involvement

- ESA Prospect Science Team - Many UK members
- Co-I on Trailblazer (NASA SIMPLEX program)
- CLPS PITMS (OU providing mass spec via ESA)
- Goonhilly ground station for lunar comm
- CNSA-ESA (Chang'e-5 collaboration)





UK Team Publications:

- Barrett, T.J., Barnes, J.J., Anand, M., Franchi, I.A., Greenwood, R.C., Charlier, B.L.A., Zhao, X., Moynier, F., Grady, M.M. (2019) Investigating magmatic processes in the early Solar System using the Cl isotopic systematics of eucrites. Geochim Cosmochim Ac https://doi.org/10.1016/j.gca.2019.06.024

- Černok, Ana; White, Lee Francis; Darling, James; Dunlop, Joseph and Anand, Mahesh (2019). Shock-induced microtextures in lunar apatite and merrillite. Meteoritics & Planetary Science, 54(6) pp. 1262–1282.

- Curran N. M., K. H. Joy, J.F. Snape, J. F. Pernet-Fisher, J. D. Gilmour, A. A. Nemchin, M. J. Whitehouse, and R. Burgess. (2019) The Early Geological History of the Moon Inferred from Ancient Lunar Meteorite Miller Range 13317. Meteoritics and Planetary Science. DOI: 10.1111/maps.13295.

- Curran, N. M., Nottingham, M., Alexander, L., Crawford, I. A., Füri, E., & Joy, K. H. (2019). A database of noble gases in lunar samples in preparation for mass spectrometry on the Moon. Planetary and Space Science, 104823.

- Deutsch, A.N., Neumann, G.A., Head, J.W. and Wilson, L. (2019) GRAIL-identified gravity anomalies in Oceanus Procellarum: insight into subsurface impact and magmatic structures on the Moon. Icarus, 331, 192-208, doi:10.1016/j.icarus.2019.05.027.

- Head, J.W. & Wilson, L. (2019) Magmatic intrusion-related processes in the upper lunar crust: the role of country rock porosity/permeability in magmatic percolation and thermal annealing, and implications for gravity signatures. Planetary and Space Science. published online. https://doi.org/10.1016/j.pss.2019.104765

- Just, G. H., Smith, K., Joy, K. H., & Roy, M. J. (2019). Parametric review of existing regolith excavation techniques for lunar In Situ Resource Utilisation (ISRU) and recommendations for future excavation experiments. Planetary and Space Science, 104746.

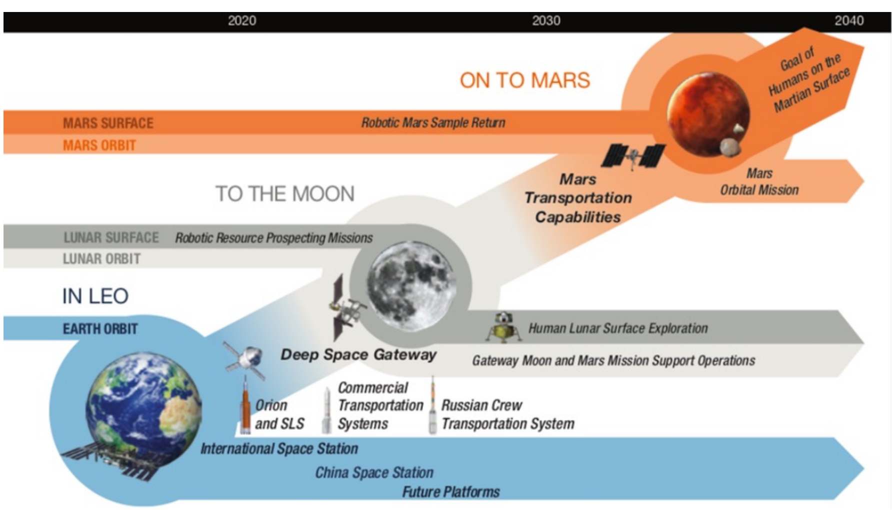
- Lim, S. and Anand, M. (2019) Numerical modelling of the microwave heating behaviour of lunar regolith. Planet Space Sci https://doi.org/10.1016/j.pss.2019.104723.

- Mouginis-Mark, P.J. & Wilson, L. (2019) Late-stage intrusive activity at Olympus Mons, Mars: summit inflation and giant dike formation. Icarus, 319, 459-469, doi:10.1016/j.icarus.2018.09.038

- Qiao, L., Head, J.W., Ling, Z., Wilson, L., Xiao, L., Dufek, J.D. & Yan, J. (2019) Geological characterization of the Ina shield volcano summit pit crater on the Moon: evidence for extrusion of waning-stage lava lake magmatic foams and anomalously young crater retention ages. Journal of Geophysical Research - Planets, 124, 1100-1140, doi:10.1029/2018JE005841

- Pernet-Fisher J. F., E. Deloule, Joy K. H. (2019) Evidence of chemical heterogeneity within lunar anorthosite parental magmas. Geochimica Cosmochimica Acta. doi.org/10.1016/j.gca.2019.03.033.

- Pernet-Fisher, J. F., McDonald, F. E., Zeigler, R. A., & Joy, K. H. (2019).



A century of lunar science and exploration in the UK: historical perspective on the last 50 years and vision for the next 50 years. Image Credit: ISECG.

50 years on: legacies of the Apollo programme. Astronomy & Geophysics, 60(4), 4-22.

- Sefton-Nash, E., Williams, J-P., Greenhagen, B. T., Warren, T. J., Bandfield, J. L., Aye, K-M., Leader, F., Siegler, M. A., Hayne, P. O., Bowles, N., Paige, D. A. (2019) Evidence for ultra-cold traps and surface water ice in the lunar south polar crater Amundsen, Icarus (2019) in press.

- Stephant, A., Anand, M., et al (2019) An ancient reservoir of volatiles in the Moon sampled by lunar meteorite Northwest Africa 10989. Geochim Cosmochim Ac https://doi.org/10.1016/j.gca.2019.07.045.

- Stephant, A., Anand, M., Zhao, X., Chan, Q. H. S., Bonifacie, M. and Franchi, I.A. (2019) The chlorine isotopic composition of the Moon: Insights from melt inclusions. Earth Planet Sc Lett 523, 115715.

- Snape, J.F., Nemchin, A.A., Whitehouse, M.J., Merle, R.E., Hopkinson, T., Anand, M. (2019) The timing of basaltic volcanism at the Apollo landing sites. Geochim Cosmochim Ac https://doi.org/10.1016/j.gca.2019.07.042.

- Tartèse, Romain; Anand, Mahesh and Franchi, Ian (2019). H and Cl isotope characteristics of indigenous and late hydrothermal fluids on the differentiated asteroidal parent body of Grave Nunataks 06128. Geochimica et Cosmochimica Acta. https://doi.org/10.1016/j.gca.2019.01.024

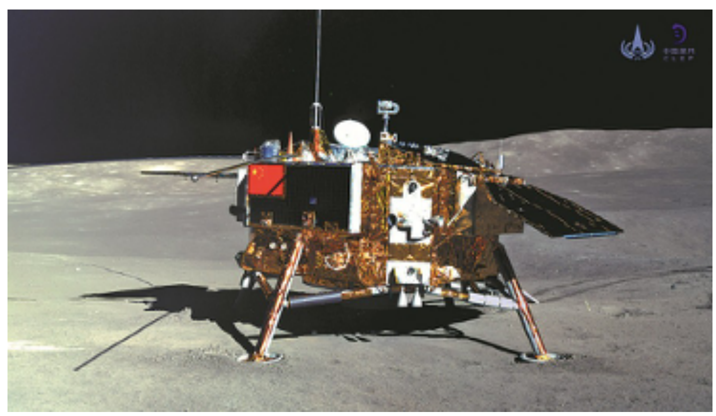
- Tartèse, R., Anand, M., Gattacceca, J., Joy, K. H., Mortimer, J. I., Pernet-Fisher, J.F., & Weiss, B. P. (2019). Constraining the Evolutionary History of the Moon and the Inner Solar System: A Case for New Returned Lunar Samples. Space Science Reviews, 215(8), 54.

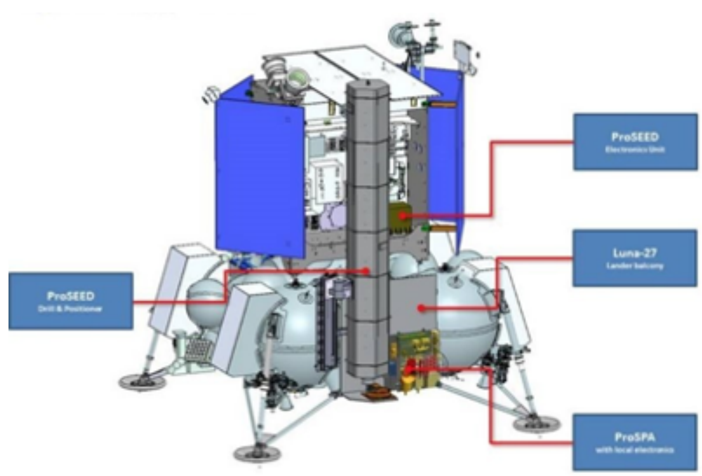
- Warren, T. J., Bowles, N. E., K. Donaldson Hanna, J. L. Bandfield (2019), Modeling the Angular Dependence of Emissivity of Randomly Rough Surfaces. JGR Planets, 124 (2019) 585-601, DOI: 10.1029/2018JE005840

- Wilson, L., Head, J.W. and Zhang, F. (2019) A theoretical model for the formation of ring moat dome structures: products of second boiling in the distal parts of lunar basaltic lava flows. Journal of Volcanology and Geothermal Research, 374, 160-180, doi:10.1016/j.jvolgeores.2019.02.018

- White, L.F., Moser, D.E., Tait, K.T., Langelier, B., Barker, I. and Darling, J.R. (2019). Crystallisation and impact history of a meteoritic sample of early lunar crust (NWA 3163) refined by atom probe geochronology. Geoscience Frontiers, DOI: 10.1016/j.gsf.2018.11.005.

- Zeng, X., Li, S., Joy, K. H., Li, X., Liu, J., Li, Y., & Wang, S. (2019). Occurrence and implications of secondary olivine veinlets in lunar highland breccia Northwest Africa 11273. Meteoritics & Planetary Science.





SSERVI TEAM PUBLICATIONS IN 2019

The following list of 129 publications was compiled from all SSERVI teams for 2019, bringing the total for year 1 through year 6 to 934.

1. Atkinson, J., Prasad, M., Abbud-Madrid, A., & Dreyer, C. B. (2019). Penetration and relaxation behavior of dry lunar regolith simulants. Icarus. 328, 82–92. doi: 10.1016/j.icarus.2019.03.009.

2. Basilevsky, A. T., Krasilnikov, S. S., Ivanov, M. A., Malenkov, M. I., Michael, G. G., Liu, T., ... & Lark, L. (2019). Potential Lunar Base on Mons Malapert: Topographic, Geologic and Trafficability Considerations. Solar System Research, 53(5), 383-398. doi: 10.1134/S0038094619050022.

3. Beaton, K. H., Chappell, S. P., Abercromby, A. F. J., Miller, M. J., Kobs Nawotniak, S. E., Brady, A. L., ... & Lim, D. S. S. (2019). Assessing the acceptability of science operations concepts and the level of mission enhancement of capabilities for human Mars exploration extravehicular activity. Astrobiology, 19(3), 321-346. doi:10.1089/ast.2018.1912.

4. Beaton, K. H., Chappell, S. P., Abercromby, A. F., Miller, M. J., Kobs Nawotniak, S. E., Brady, A. L., ... & Lim, D. S. (2019). Using science-driven analog research to investigate extravehicular activity science operations concepts and capabilities for human planetary exploration. Astrobiology, 19(3), 300-320. doi:10.1089/ast.2018.1861.

5. Bellucci, J. J., Nemchin, A. A., Grange, M., Robinson, K. L., Collins, G., Whitehouse, M. J., ... & Kring, D. A. (2019). Terrestrial-like zircon in a clast from an Apollo 14 breccia. Earth and Planetary Science Letters, 510, 173-185. doi: 10.1016/j.epsl.2019.01.010.

6. Benna, M, Hurley, D. M., Stubbs, T. J., et al. (2019), Lunar soil hydration constrained by exospheric water liberated by meteoric impacts, Nature Geoscience, 12, 333-338. doi:10.1038/s41561-019-0345-3.

7. Bermingham, K. R., Walker, R. J., & Worsham, E. A. (2016). Refinement of high precision Ru isotope analysis using negative thermal ionization mass spectrometry. International journal of mass spectrometry, 403, 15-26. Doi: 10.1016/j.ijms.2016.02.003.

8. Bermingham, K. R., Worsham, E. A., & Walker, R. J. (2018). New insights into Mo and Ru isotope variation in the nebula and terrestrial planet accretionary genetics. Earth and planetary science letters, 487, 221-229. Doi: 10.1016/j.epsl.2018.01.017

9. Bernardoni, E. A., Szalay, J. R., & Horányi, M. (2019) Impact Ejecta Plumes at the Moon. Geophysical Research Letters, 46(2), 534-543. doi: 10.1029/2018GL079994.

10. Bickel, V. T., Honniball, C. I., Martinez, S. N., Rogaski, A., Sargeant, H. M., Bell, S. K., ... & Kring, D. A. (2019). Analysis of Lunar Boulder Tracks: Implications for Trafficability of Pyroclastic Deposits. Journal of Geophysical Research: Planets, TBD. doi: 10.1029/2018JE005876.

11. Brady, A. L., Kobs Nawotniak, S. E., Hughes, S. S., Payler, S. J., Stevens, A. H., Cockell, C. S., ... & Lim, D. S. (2019). Strategic planning insights for future science-driven extravehicular activity on Mars. Astrobiology, 19(3), 347-368.

doi:10.1089/ast.2018.1850.

12. Britt D.T., Cannon K.M., Donaldson Hanna K., Hogancamp J., Poch O., Beck P., Martin D., Escrig J., Bonal L., and Metzger P.T. (2019) Simulated asteroid materials based on carbonaceous chondrite mineralogies. Meteoritics. doi: 10.1111/maps.13345.

13. Burney & Neal (2019) Method for quantifying and removing polyatomic interferences on a suite of moderately volatile elements (Zn, Se, Rb, Ag, Cd, In, Sb, Tl, Pb, and Bi) during solution-mode ICP-MS, J. Anal. At. Spectrom. doi:10.1039/c9/a00003h.

14. Burns, J., Hallinan, G., Lux, J., Romero-Wolf, A., Chang, T. C., Kocz, J., ... & Anderson, M. (2019). FARSIDE: A Low Radio Frequency Interferometric Array on the Lunar Farside. arXiv:1907.05407.

15. Burns, J.O. Bale, S., Bassett, N., Bowman, J., Bradley, R. Flalkov, A., ... & MacDowal, R. (2019) Dark Cosmology: Investigating Dark Matter & Exoctic Physics in the Dark Ages using the Redshifted 21-cm Global Spectrum. arXiv preprint arXiv:1902.06147.

16. Burns, J.O., Mellinkoff, B., Spydell, M., Fong, T., Kring, D.A., Pratt, W.D., Cichan, T. and Edwards, C.M. (2019) Science on the lunar surface facilitated by low latency telerobotics from a Lunar Orbital Platform-Gateway. Acta Astronautica, 154, pp.195-203. doi: 10.1016/j.actaastro.2018.04.031.

17. Cahill J.T.S., A.A. Wirth, A.R. Hendrix, K.D. Rutherford, T.K. Greathouse, K.E. Mandt, Y. Liu, B.T. Greenhagen, B.W. Denevi, A.M. Stickle, and D.M. Hurley (2019) An Examination of Several Discrete Lunar Nearside Photometric Anomalies Observed in Lyman- Maps, JGR Planets, 124. doi: 10.1029/2018JE005754.

18. Cahill, J. T. S., D. T. Blewett, N. V. Nguyen, A. Boosalis, S. J. Lawrence, and B. W. Denevi (2019), Optical constants of iron and nickel metal an assessment of their relative influences on silicate mixture spectral from the FUV to the NIR, Icarus, 317. Doi:10.1016/j.icarus.2018.1007.1008.

19. Caldwell, Barrett S., NYRE-YU Megan, and R. Jordan. “Advances in Human-Automation Collaboration, Coordination and Dynamic Function Allocation.” Transdisciplinary Engineering for Complex Socio-technical Systems: Proceedings of the 26th ISTE International Conference on Transdisciplinary Engineering, July 30–August 1, 2019. Vol. 10. IOS Press, 2019.

20. Carballido, A., Desch, S. J., & Taylor, G. J. (2016). Magneto-rotational instability in the protolunar disk. Icarus, 268, 89-101. doi: 10.1016/j.icarus.2015.12.042

21. Chen, X., Burns, J., Koopmans, L., Rothkaehi, H., Silk, J., Wu, J., ... & Deng, L. (2019). Discovering the Sky at the Longest Wavelengths with Small Satellite Constellations. arXiv preprint. arXiv:1907.10853.

22. Christou, Apostolos, A., Jeremie Vaubaillon, Paul Withers, Ricardo Hueso and Rosemary Killen (2019). Extra-terrestrial Meteors. In: Meteoroids: Sources of Meteors on Earth and Beyond, [Galina O. Ryabova, David J. Asher and Margaret Campbell-Brown, Eds], Cambridge Planetary Science series.

23. Clement, M. S., Kaib, N. A., Raymond, S. N., Chambers, J. E., Walsh, K. J. 2019. The early instability scenario: Terrestrial planet formation during the giant planet instability, and the effect of collisional fragmentation.Icarus 321, 778-790. Doi: 10.1016/j.icarus.2018.12.033.

24. Clement, M. S., Kaib, N. A., Raymond, S. N., Chambers, J. E., & Walsh, K. J. (2019). The early instability scenario: Terrestrial planet formation during the giant planet instability, and the effect of collisional fragmentation. Icarus, 321,

778-790. doi: 10.1016/j.icarus.2018.12.033.

25. Cloutis, E., P. Beck, J.J. Gillis-Davis, J. Helbert, and M.J. Loeffler (2019) Chapter 13: Effects of Environmental Conditions on Spectral Measurements. In: Remote Compositional Analysis: Techniques for Understanding Spectroscopy, Mineralogy, and Geochemistry of Planetary Surfaces (Editors: J.L. Bishop, J.F. Bell III, and J.E. Moersch) pp. 289- 306; Cambridge University Press; ISBN 9781107186200. doi: 10.1017/978131688887.

26. Cockell, C. S., Harrison, J. P., Stevens, A. H., Payler, S. J., Hughes, S. S., Kobs Nawotniak, S. E., ... & Beaton, K. H. (2019). A low-diversity microbiota inhabits extreme terrestrial basaltic terrains and their fumaroles: implications for the exploration of Mars. Astrobiology, 19(3), 284-299. doi:10.1089/ast.2018.1870.

27. Cohen, B. A., Szalay, J. R., Rivkin, A. S., Richardson, J. A., Klima, R. L., Ernst, C. M., ... & Horányi, M. (2019). Using dust shed from asteroids as microsamples to link remote measurements with meteorite classes. Meteoritics & Planetary Science, 54(9), 2046-2066. doi: 10.1111/maps.13348.

28. Hahn D., Jayasena, B., Jiang, Z., and Melkote, S.N. (2019). Polymer stamp-based mechanical exfoliation of thin high-quality pyrolytic graphite sheets. J. Micro Nano-Manuf. 7(1). doi: 10.1115/1.4043502

29. DeMeo, F. E., D. Polishook, B. Carry, B. J. Burt, H. H. Hsieh, R. P. Binzel, N. A. Moskovitz, and T. H. Burbine (2019), Olivine-dominated A-type asteroids in the main belt: Distribution, abundance and relation to families, Icarus, 322, 13-30. doi: 10.1016/j.icarus.2018.12.016.

30. Deutsch, A. N., G. A. Neumann, J. W. Head, and L. Wilson (2019), GRAIL-identified gravity anomalies in Oceanus Procellarum: Insight into subsurface impact and magmatic structures on the Moon, Icarus 331, 192-208. doi: 10.1016/j.icarus.2019.05.027.

31. Deutsch, A. N., J. W. Head, and G. A. Neumann (2019), Age constraints of Mercury's polar deposits suggest recent delivery of ice. Earth Planet. Sci. Lett., 520, 26–33. doi: 10.1016/j.epsl.2019.05.027.

32. Donaldson Hanna K.L., B.T. Greenhagen, W.R. Patterson, C.M.Pieters, J.F. Mustard, N.E. Bowles, D.A. Paige, T.D. Glotch, and C. Thompson (2016) Effects of varying environmental conditions on emissivity spectra of bulk lunar soils: Application to Diviner thermal infrared observations of the Moon, Icarus, 283, 326-342. doi: 10.1016/j.icarus.2016.05.034.

33. Doule, O., Kiss, D. V., Mehta, Y., Crisman, K., Beltran, E., & Miller, M. (2019). Design and Operational Considerations for Human Spaceflight Occupant Safety. New Space, 7(2), 67-78. doi: 10.1089/newspace.2018.0033.

34. Eastwood, M.W., Anderson, M.M., Monroe, R.M., Hallinan, G., Catha, M., Dowell, J., Garsden, H., Greenhill, L.J., Hicks, B.C., Kocz, J., Price, D.C., Schinzel, F. K., Vedantham, and Wang. Y. (2019). The 21 cm Power Spectrum from the Cosmic Dawn: First Results from the OVRO-LWA. The Astronomical Journal, 158 (2). doi: 10.3847/1538-3881/ab2629.

35. El Mir, C., Delbo, M., and Ramesh, K.T. (2019). The efficiency of thermal fatigue in regolith generation on small airless bodies. Icarus, 333, 356-370. doi: 10.1016/j.icarus.2019.06.001.

36. El Mir, C., Ramesh, K.T., and Richardson, D.C. (2019). A new hybrid framework for simulating hypervelocity asteroid impacts and gravitational re-accumulation. Icarus, Vol. 321, pp. 1013-1025. doi: 10.1016/j.icarus.2018.12.032.

37. Erickson, T. M., Timms, N. E., Pearce, M. A., Cayron, C., Deutsch, A., Keller, L. P., & Kring, D. A. (2019). Shock-produced high-pressure (La, Ce, Th) PO4 polymorph revealed by microstructural phase heritage of monazite. Geology,

47(6), 504-508. doi: 10.1130/G46008.1.

38. Farrell W. M., D. M. Hurley, M. J. Poston, P. O. Hayne, J. R. Szalay, and J. L. McLain (2019). The young age of the LAMP-observed frost in lunar polar craters, Geophysical Research Letters, 46, 8680–8688. doi:10.1029/2019GL083158.

39. Fisher E.A., P.G. Lucey, M. Lemelin, B.T. Greenhagen, M.A. Siegler, E. Mazarico, O. Aharonson, J.-P. Williams, P.O. Hayne, G.A. Neumann, D.A. Paige, D.E. Smith, M.T. Zuber (2017) Evidence for surface water ice in the lunar polar regions using reflectance measurements from the Lunar Orbiter Laser Altimeter and temperature measurements from the Diviner Lunar Radiometer Experiment, Icarus, 292, 74-85. doi: 10.1016/j.icarus.2017.03.023.

40. Futaana, Y., Barabash, S., Wieser, M., Wurz, P., Hurley, D., Horányi, M., ... & Retherford, K. (2018). SELMA mission: How do airless bodies interact with space environment? The Moon as an accessible laboratory. Planetary and space science, 156, 23-40. doi: 10.1016/j.pss.2017.11.002.

41. Golubov, O., and D.J. Scheeres. (2019). Systematic structure and sinks in the YORP effect. The Astrophysical Journal 157(3), 105. doi: 10.3847/1538-3881/aafd2c.

42. Hartzell, C. M. (2019). Dynamics of 2D electrostatic dust levitated at asteroids, Icarus, 333, 234-242. doi: 10.1016/j.icarus.2019.05.013.

43. Hayne P.O., J.L. Bandfield, M.A. Siegler, A.R. Vasavada, R.R. Ghent, J.-P. Williams, B.T. Greenhagen, O. Aharonson, C.M. Elder, P.G. Lucey, and D.A. Paige (2017) Global Regolith Thermophysical Properties of the Moon From the Diviner Lunar Radiometer Experiment, JGR Planets, 122. doi.org/10.1002/2017JE005387.

44. Hendrix, A. R. and F. Vilas (2019) C-complex asteroids: UV-visible spectral characteristics and implications for space weathering effects. GRL. doi: 10.1029/2019GL085883.

45. Hendrix A. R., D. M. Hurley, W. M. Farrell, et al. (2019), Diurnally migrating lunar water: Evidence from ultraviolet data, Geophys. Res. Lett., 46, 2417-2424. doi: 10.1029/2018GL081821.

46. Hill, J. R., Caldwell, B. S., Miller, M. J., & Lees, D. S. (2016, July). Data integration and knowledge coordination for planetary exploration traverses. In International Conference on Human Interface and the Management of Information (pp. 414-422). Springer, Cham. doi: 10.1007/978-3-319-40397-7_39.

47. Hill, J. R., Caldwell, B. S., Downs, M., Miller, M. J., & Lim, D. S. (2018). Remote physiological monitoring in a Mars Analog field setting. IISE Transactions on Healthcare Systems Engineering, 8(3), 227-236. doi: 10.1080/24725579.2018.1501624

48. Hill, J. R., & Caldwell, B. S. (2019, November). A Bootstrap Method for the Analysis of Physiological Data in Uncontrolled Settings. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 63, No. 1, pp. 136-140). Sage CA: Los Angeles, CA: SAGE Publications. doi: 10.1177/1071181319631229.

49. Hill, J. R., & Caldwell, B. S. (2018, September). Toward better understanding of function allocation requirements for planetary EVA and habitat tasks. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 62, No. 1, pp. 29-33). Sage CA: Los Angeles, CA: SAGE Publications.

50. Hodges, K., and H. Schmitt. Imagining a new era of planetary field geology. Science Advances 11 Sep 2019: Vol. 5, no. 9, eaaz2484. doi: 10.1126/sciadv.aaz2484.

51. Hughes, S. S., Haberle, C. W., Kobs Nawotniak, S. E., Sehlke, A., Garry, W. B., Elphic, R. C., ... & Heldmann, J. L.

(2019). Basaltic terrains in Idaho and Hawai ‘i as planetary analogs for Mars geology and astrobiology. Astrobiology, 19(3), 260-283. doi: 10.1089/ast.2018.1847.

52. Jansen, J. C., J. C. Andrews-Hanna, C. Milbury, J. W. Head III, Y. Li, H. J. Melosh, and M. T. Zuber (2019), Radial gravity anomalies associated with ejecta of the Orientale basin, Icarus, 319, 444-458. doi: 10.1016/j.icarus.2018.09.034.

53. Jarmak, S., J. Brisset, J. Colwell, A. Dove, D. Maukonen, S. A. Rawashdeh, J. Blum, L. Roe (2019). CubeSat Particle Aggregation Collision Experiment (Q-PACE): Design of a 3U CubeSat mission to investigate planetesimal formation. Acta Astronautica, 155, 131-142. doi: 10.1016/j.actastro.2018.11.029.

54. Jawin E.R., Valencia, S.N., Watkins R.N., Crowell J.M., Neal C.R., and Schmidt G. (2019) Lunar Science for Landed Missions Workshop Findings Report Earth and Space Science, 6. doi:10.1029/2018EA000490.

55. Jiang, Y., Lu, Z., Gigliotti, J., Rustagi, A., Chen, L., Berger, C., ... & Jiang, Z. (2019). Valley and Zeeman Splittings in Multilayer Epitaxial Graphene Revealed by Circular Polarization Resolved Magneto-infrared Spectroscopy. Nano letters, 19(10), 7043-7049. doi: 10.1021/acs.nanolett.9b02505.

56. Keller, C. B., J. M. Husson, R. N. Mitchell, W. F. Bottke, T. M. Gernon, P. Boehnke, E. A. Bell, N. L. Swanson-Hysell, and S. E. Peters. (2019) Neoproterozoic glacial origin of the Great Unconformity. Proceedings of the National Academy of Science 116 (4) 1136-1145. doi:10.1073/pnas.1804350116.

57. Killen, R. M., Morgan, T. H., Potter, A. E., et al. (2019), Coronagraphic observations of the lunar sodium exosphere January-June, 2017, Icarus, 328, 152-159. doi:10.1016/j.icarus.2019.02.027.

58. Killen, Rosemary M., David R. Williams, Jaekyun Park, Orenthal J. Tucker,Sang-Joon Kim (2019). The lunar exosphere seen in LACE data, Icarus, 329, 246-250. doi: 10.1016/j.icarus.2019.04.018.

59. Kyeong J. Kim, Christian Wöhler, Alexey A. Berezhnoy, Megha Bhatt, Arne Grumpe (2019) Prospective 3He-rich landing sites on the Moon, Planetary and Space Science, Volume 177. doi: 10.1016/j.pss.2019.07.001.

60. Kitazato, K., Milliken, R. E., Iwata, T., Abe, M., Ohtake, M., Matsuura, S., ... & Senshu, H. (2019). The surface composition of asteroid 162173 Ryugu from Hayabusa2 near-infrared spectroscopy. Science, eaav7432. doi: 10.1126/science.aav7432.

61. Kobs Nawotniak, S. E., Miller, M. J., Stevens, A. H., Marquez, J. J., Payler, S. J., Brady, A. L., ... & Chappell, S. P. (2019). Opportunities and challenges of promoting scientific dialog throughout execution of future science-driven extravehicular activity. Astrobiology, 19(3), 426-439. doi:10.1089/ast.2018.1901.

62. Koopmans, L., Barkana, R., Bentum, M., Bernardi, G., Boonstra, A. J., Bowman, J., ... & Fialkov, A. (2019). Peering into the Dark (Ages) with Low-Frequency Space Interferometers. arXiv preprint arXiv:1908.04296.

63. Lepaulard, C., Gattacceca, J., Uehara, M., Rochette, P., Quesnel, Y., Macke, R. J., & Kiefer, S. W. (2019). A survey of the natural remanent magnetization and magnetic susceptibility of Apollo whole rocks. Physics of the Earth and Planetary Interiors, 290, 36-43. doi: 10.1016/j.pepi.2019.03.004.

64. Li, M., Thompson, K. K., Nissen, J. C., Hendrix, D., Hurowitz, J. A., & Tsirka, S. E. (2019). Lunar soil simulants alter macrophage survival and function. Journal of Applied Toxicology, 39(10), 1413-1423. doi: 10.1002/jat.3827.

65. Lim, D. S., Abercromby, A. F., Kobs Nawotniak, S. E., Lees, D. S., Miller, M. J., Brady, A. L., ... & Stevens, A. H. (2019). The BASALT research program: designing and developing mission elements in support of human scientific exploration

of Mars. Astrobiology, 19(3), 245-259. doi:10.1089/ast.2018.1869.

66. Lo, Y. H., Liao, C. T., Zhou, J.,Rana, A., Bevis, C.S., Gui, G., Enders, B., Cannon, K., Yu, Y., Celestre, R., Kapteyn, K., Falcone, R., Bennett, C, Murnane, M., (2019) Multimodal x-ray and electron microscopy of the Allende meteorite. Science Advances 5(9) eaax3009. doi: 10.1126/sciadv.aax3009.

67. Lucas, M. P., J. P. Emery, T. Hiroi, and H. Y. McSween Jr. (2019), Spectral properties and mineral compositions of acapulcoite-lodranite clan meteorites: Establishing S-type asteroid-meteorite connections, Meteoritics & Planetary Science, 54, 157-180. doi: 10.1111/maps.13203.

68. Lucey P.G., B.T. Greenhagen, E. Song, J.A. Arnold, M. Lemelin, K.L. Donaldson Hanna, N.E. Bowles, T.D. Glotch, D.A. Paige (2016) Space weathering effects in Diviner Lunar Radiometer multispectral infrared measurements of the lunar Christiansen Feature: Characteristics and mitigation, Icarus, 283, 343-351. doi: 10.1016/j.icarus.2016.05.010.

69. MacGregor, J. A., Bottke Jr, W. F., Fahnestock, M. A., Harbeck, J. P., Kjær, K. H., Paden, J. D., ... & Studinger, M. (2019). A possible second large subglacial impact crater in northwest Greenland. Geophysical Research Letters, 46(3), 1496-1504. doi: 10.1029/2018GL078126.

70. Marquez, J. J., Miller, M. J., Cohen, T., Deliz, I., Lees, D. S., Zheng, J., ... & Hillenius, S. (2019). Future needs for science-driven geospatial and temporal extravehicular activity planning and execution. Astrobiology, 19(3), 440-461. doi:10.1089/ast.2018.1838.

71. Mazrouei, S., Ghent, R. R., Bottke, W. F., Parker, A. H., & Gernon, T. M. (2019). Earth and Moon impact flux increased at the end of the Paleozoic. Science, 363(6424), 253-257. doi: 10.1126/science.aar4058.

72. Mebane, R. H., Mirocha, J., & Furlanetto, S. R. (2019). The Effects of Population III X-ray and Radio Backgrounds on the Cosmological 21-cm Signal. doi: 10.1093/mnras/staa280.

73. Metzger P.T., Britt D.T., Covey S.D., Schultz C., Cannon K.M., Grossman K.D., Mantovani J.G., and Mueller R.P. (2019) Measuring the fidelity of asteroid regolith and cobble simulants. Icarus 321, 632-646. doi: 10.1016/j.icarus.2018.12.019.

74. Miller, M. J., Miller, M. J., Santiago-Materese, D., Seibert, M. A., & Lim, D. S. (2019). A flexible telecommunication architecture for human planetary exploration based on the BASALT science-driven Mars analog. Astrobiology, 19(3), 478-496. doi:10.1089/ast.2018.1906.

75. Monsalve, R. A., Fialkov, A., Bowman, J. D., Rogers, A. E., Mozdzen, T. J., Cohen, A., ... & Mahesh, N. (2019). Results from EDGES High-Band: III. New Constraints on Parameters of the Early Universe. The Astrophysics Journal, 875(1), 67. doi: 10.3847/1538-4357/ab07be.

76. Mustard, J. F., and T. D. Glotch (2019), Chapter 2: Theory of Emittance and Reflectance Spectroscopy of Geologic Materials in the Visible and Infrared Regions. In: Remote Compositional Analysis: Techniques for Understanding Spectroscopy, Mineralogy, and Geochemistry of Planetary Surfaces (Editors: J.L. Bishop, J.F. Bell III, and J.E. Moersch) pp. 289-306; Cambridge University Press; ISBN 9781107186200. doi: 10.1017/9781316888872.

77. Neal, C. R., Schmidt, G. K., Ehrenfreund, P., & Carpenter, J. D. (2014). Developing the global exploration roadmap: An example using the humans to the lunar surface theme. Space Policy, 30(3), 156-162. Doi: 10.1016/j.spacepol.2014.08.007

78. Nénon, Q., Poppe, A. R., Rahmati, A.,Lee, C. O., McFadden, J. P., & Fowler,C. M. (2019). Phobos surface sputteringas

inferred from MAVEN ion observations. Journal of Geophysical Research: Planets,124. doi: 10.1029/2019JE006197.

79. Nesvorný, D., Li, R., Youdin, A.N., Simon. J. B., and Grundy, W. M. (2019). TTrans-Neptunian binaries as evidence for planetesimal formation by the streaming instability. Nature Astronomy. doi: 10.1038/s41550-019-0806-z

80. Niihara, T., Beard, S. P., Swindle, T. D., Schaffer, L. A., Miyamoto, H., & Kring, D. A. (2019). Evidence for multiple 4.0–3.7 Ga impact events within the Apollo 16 collection. Meteoritics & Planetary Science, 54(4),675-698. doi: 10.1111/maps.13237.

81. Orgel, C., Michael, G., Fassett, C. I., van der Bogert, C. H., Riedel, C., Kneissl, T., & Hiesinger, H. (2018). Ancient bombardment of the inner solar system: Reinvestigation of the “fingerprints” of different impactor populations on the lunar surface. Journal of Geophysical Research: Planets, 123(3), 748-762. Doi: 10.1002/2017JE005451

82. Palomba, E., A. Longobardo, M.C. De Sanctis, N.T. Stein, B. Ehlmann, A. Galiano, A. Raponi, M. Ciarniello, E. Ammannito, E. Cloutis, F.G. Carrozzo, M. T. Capria, K. Stephan, F. Zambon, F. Tosi, C.A. Raymond, and C.T. Russell (2019) Compositional differences among Bright Spots on the Ceres surface. Icarus, 320, 202-212. doi: 10.1016/j.icarus.2017.09.020.

83. Pasckert, J. H., Hiesinger, H., & van der Bogert, C. H. (2018). Lunar farside volcanism in and around the South Pole–Aitken basin. Icarus, 299, 538-562. Doi: 10.1016/j.icarus.2017.07.023

84. Payler, S. J., Mirmalek, Z., Hughes, S. S., Kobs Nawotniak, S. E., Brady, A. L., Stevens, A. H., ... & Lim, D. S. S. (2019). Developing intra-EVA science support team practices for a human mission to Mars. Astrobiology, 19(3), 387-400. doi:10.1089/ast.2018.1846.

85. Pokorný, P., Janches, D., Sarantos, M., Szalay, J. R., Horányi, M., Nesvorný, D., & Kuchner, M. J. (2019). Meteoroids at the Moon: Orbital Properties, Surface Vaporization, and Impact Ejecta Production. Journal of Geophysical Research: Planets. 124, 752-778. doi:10.1029/2018JE005912.

86. Poppe A. R. (2019). Comment on “The dominant role of energetic ions in solar wind interaction with the Moon” by Omidi et al.. Journal of Geophysical Research: Space Physics, 124. doi: 10.1029/2019JA02669692.

87. Povilaitis, R. Z., Robinson, M. S., Van der Bogert, C. H., Hiesinger, H., Meyer, H. M., & Ostrach, L. R. (2018). Crater density differences: Exploring regional resurfacing, secondary crater populations, and crater saturation equilibrium on the moon. Planetary and Space Science, 162, 41-51. Doi: 10.1016/j.pss.2017.05.006

88. Prem, P., Goldstein, D. B., Varghese, P. L., and Trafton, L. M. (2019), Coupled DSMC-Monte Carlo radiative transfer modeling of gas dynamics in a transient impact-generated lunar atmosphere, Icarus, 326, 88-104. doi:10.1016/j.icarus.2019.02.036.

89. Qiao, L., J. W. Head III, Z. Ling, L. Wilson, L. Xiao, J. D. Dufek, and J. Yan (2019), Geological characterization of the Ina shield volcano summit pit crater on the Moon: Evidence for extrusion of waning-stage lava lake magmatic foams and anomalously young crater retention ages, J. Geophys. Res., 124, 1100-1140. doi: 10.1029/2018JE005841.

90. Ramsley, K., and J. W. Head III (2019), Origin of Phobos grooves: Testing the Stickney crater ejecta model, Planetary and Space Science, 165, 137-147. doi: 10.1016/j.pss.2018.11.004.

91. Reddy, V., Sanchez, J. A., Furfaro, R., Binzel, R. P., Burbine, T. H., Le Corre, L., ... & Brozovic, M. (2018). Surface Composition of (99942) Apophis. The Astronomical Journal, 155(3), 140. doi: 10.3847/1538.3881/aaaalc.

92. Rhodes, D. J, and W. M. Farrell (2019). Steady-state solution of a solar-wind generated electron cloud in a lunar crater, J. Geophys. Res. Space Physics, 124, 4983-4993. doi:10.1029/2019JA026625.

93. Riedel, Christian, et al. “A New Tool to Account for Crater Obliteration Effects in Crater Size-Frequency Distribution Measurements.” Earth and Space Science 5.6 (2018): 258-267. Doi: 10.1002/2018EA000383

94. Righter, K., Cosca, M. A., & Morgan, L. E. (2016). Preservation of ancient impact ages on the R chondrite parent body: 40Ar/39Ar age of hornblende-bearing R chondrite LAP 04840. Meteoritics & Planetary Science, 51(9), 1678-1684. Doi: 10.1111/maps.12692

95. Robbins, S.J. (2019) A New Global Database of Moon Impact Craters >1–2 km: 1. Crater Locations and Sizes, Properties, and Comparisons with Published Databases. J. Geophys. Res. Planets. doi: 10.1029/2018JE005592.

96. Roberts, S. E. and Neal, C. R. (2019) Origin of lunar Very High Potassium (VHK) basalts: A combination of endogenous and exogenous processes. Geochimica et Cosmochimica Acta 266, 54–73. doi: 10.1016/j.gca.2019.01.023.

97. Salmon, J., & Canup, R. M. (2019). HydroSyMBA: a 1D hydrocode coupled with an N-body symplectic integrator. The Astrophysics Journal, 881:129-137. doi: 10.3847/1538-4357/ab2b96

98. Samaniego, J. I., Wang, X., Andersson, L., Malaspina, D., Ergun, R. E., & Horanyi, M., (2019) Investigation of coatings for Langmuir probes: Effect of surface oxidation on photoemission characteristics, Journal of Geophysical Research: Space Physics, 124, 2357-2361. doi:10.1029/2018JA026127.

99. Saxena, P., Killen, R. M., Airapetian, V., Petro, N. E., Curran, N. M., & Mandell, A. M. (2019), Was the Sun a Slow Rotator? Sodium and Potassium Constraints from the Lunar Regolith. The Astrophysical Journal Letters, 876(1), L16. doi: 10.3847/2041-8213/ab18fb.

100. Scheeres, D. J., Olikara, Z., & Baresi, N. (2019). Dynamics in the Phobos environment. Advances in Space Research, 63(1), 476-495. doi: 10.1016/j.asr.2018.10.016.

101. Schieber, G. L., Jones, B., Orlando, T. M., & Loutzenhiser, P. G. (2019). Advection diffusion model for gas transport within a packed bed of JSC-1A regolith simulant. Acta Astronautica, 169:32-39. doi: 10.1016/j.actaastro.2019.12.031.

102. Schmieder, M., Shaulis, B. J., Lapen, T. J., Buchner, E., & Kring, D. A. (2019). In situ U–Pb analysis of shocked zircon from the Charlevoix impact structure, Québec, Canada. Meteoritics & Planetary Science, 54(8), 1808-1827. Doi:10.1111/maps.13315

103. Sefton-Nash E., J.P. Williams, B.T. Greenhagen, T.J. Warren, J.L. Bandfield, K.M. Aye, F. Leader, M.A. Siegler, P.O. Hayne, N. Bowles, and D.A. Paige (2019) Evidence for Ultra-cold Traps and Surface Water Ice in the Lunar South Polar Crater Amundsen, Icarus, 332. doi: 10.1016/j.icarus.2019.06.002.

104. Sehlke, A., Mirmalek, Z., Burtt, D., Haberle, C.W., Santiago-Materese, D., Kobs Nawotniak, S.E., Hughes, S.S., Garry, W.B., Bramall, N., Brown, A.J. and Heldmann, J.L. (2019). Requirements for portable instrument suites during human scientific exploration of Mars. Astrobiology, 19(3), 401-425. doi: 10.1089/ast.2018.1841.

105. Seibert, M. A., Lim, D. S., Miller, M. J., Santiago-Materese, D., & Downs, M. T. (2019). Developing Future Deep-Space Telecommunication Architectures: A Historical Look at the Benefits of Analog Research on the Development of Solar System Internetworking for Future Human Spaceflight. Astrobiology, 19(3), 462-477. doi:10.1089/ast.2018.1915

106. Shaner, A., Watson, S., Bakerman, M., & Buxner, S. (2018). ExMASS: A viable model for authentic student-

scientist research partnerships. Acta Astronautica, 152, 1-9. Doi: 10.1016/j.actaastro.2018.07.031

107. Sheppard, R. Y., R. E. Milliken, J. M. Russell, M. D. Dyar, E. C. Sklute, H. Vogel, M. Melles, S. Bijaksana, M. A. Morlock, and A. K. M. Hasberg (2019) Characterization of iron in Lake Towuti sediment, Chemical Geology, 512, 11-30. doi: 10.1016/j.chemgeo.2019.02.029.

108. Shirley, K. A., and T. D. Glotch (2019), Particle size effects on mid-IR spectra of lunar analog minerals in a simulated lunar environment, J. Geophys. Res.,Planets, 124(4), 970-988. doi:10.1029/2018JE005533.

109. Shkuratov, Y., Y. A. Surkov, M. A. Ivanov, V. V. Korokhin, V. G. Kaydash, G. Videen, C. M. Pieters, and D. Stankevich (2019), Improved Chandrayaan-1 M3 data: A northewest portion of the Aristarchus plateau and contiguous maria, Icarus, 321, 34-94. doi: 10.1016/j.icarus.2018.11.002.

110. Simkus, D. N., Aponte, J. C., Hilts, R. W., Elsila, J. E., & Herd, C. D. (2019). Compound-specific carbon isotope compositions of aldehydes and ketones in the Murchison meteorite. Meteoritics & Planetary Science, 54(1), 142-156. doi: 10.1111/maps.13202.

111. Stadermann, A. C., Zanetti, M. R., Jolliff, B. L., Hiesinger, H., van der Bogert, C. H., & Hamilton, C. W. (2018). The age of lunar mare basalts south of the Aristarchus Plateau and effects of secondary craters formed by the Aristarchus event. Icarus, 309, 45-60. Doi: 10.1016/j.icarus.2018.02.030

112. Stevens, A. H., Kobs Nawotniak, S. E., Garry, W. B., Payler, S. J., Brady, A. L., Miller, M. J., ... & Lim, D. S. S. (2019). Tactical scientific decision-making during crewed astrobiology Mars missions. Astrobiology, 19(3), 369-386. doi:10.1089/ast.2018.1837.

113. Sugita, S., Honda, R., Morota, T., Kameda, S., Sawada, H., Tatsumi, E., ... & Sakatani, N. (2019). The geomorphology, color, and thermal properties of Ryugu: Implications for parent-body processes. Science, 364(6437), eaaw0422. doi: 10.1126/science.aaw0422.

114. Szalay, J. R., Pokorný, P., Horányi, M., Janches, D., Sarantos, M., & Srama, R. (2019). Impact ejecta environment of an eccentric asteroid: 3200 Phaethon. Planetary and Space Science, 165, 194-204. doi: 10.1016/j.pss.2018.11.001.

115. Szalay, J. R., Pokorny, P., Sternovsky, Z., Kupihar, Z., Poppe, A. R., & Horányi, M.(2019) Impact Ejecta and Gardening in the Lunar Polar Regions. Journal of Geophysical Research: Planets, 24(1), 143-154. doi: 10.1029/2018JE005756.

116. Van Der Bogert, C. H., Clark, J. D., Hiesinger, H., Banks, M. E., Watters, T. R., & Robinson, M. S. (2018). How old are lunar lobate scarps? 1. Seismic resetting of crater size-frequency distributions. Icarus, 306, 225-242. Doi: 10.1016/j.icarus.2018.01.019

117. Walsh, K. J. (2018). Rubble pile asteroids. Annual Review of Astronomy and Astrophysics, 56, 593-624. doi: 10.1146/annurev-astro-081817-052013

118. Walsh, K. J., & Levison, H. F. (2019). Planetesimals to terrestrial planets: Collisional evolution amidst a dissipating gas disk. Icarus, 329, 88-100. doi: 10.1016/j.icarus.2019.03.031

119. Wang, X., Hood, N., Carroll, A., Mike, R., Hsu, H. W., & Horanyi, M. (2019, January). Laboratory measurements of initial conditions of electrostatically lofted dust. In Geophysical Research Abstracts, 21:1.

120. Wang, X., Robertson, S., and Horányi, M. (2019). Plasma Sheath Formation at Craters on Airless Bodies. JGR Space Physics. doi: 10.1029/2018JA026235.

121. Wei G.F., X.Y. Li, H. Gan, D.T. Blewett, C.D. Neish, and B.T. Greenhagen (2019) A New Method for Simulation of Lunar Microwave Brightness Temperatures and Evaluation of Chang'E-2 MRM Data Using Thermal Constraints From Diviner, JGR Planets, 124. doi: 10.1029/2018JE005858.

122. Williams J.P., J.L. Bandfield, D.A. Paige, T.M. Powell, B.T. Greenhagen, S. Taylor, P.O. Hayne, E.J. Speyerer, R.R. Ghent, and E.S. Costello (2018) Lunar Cold Spots and Crater Production on the Moon, JGR Planets, 123. doi:10.1029/2018JE005652.

123. Williams J.P., B.T. Greenhagen, D.A. Paige, N. Schorghofer, E. Sefton-Nash, P.O. Hayne, P.G. Lucey, M.A. Siegler, and K.M. Aye (2019) Seasonal Polar Temperatures on the Moon, JGR Planets. doi:10.1029/2019JE006028.

124. Wilson, L., J. W. Head III, and F. Zhang (2019), A theoretical model for the formation of Ring Moat Dome Structures: Products of second boiling in lunar basaltic lava flows, J Volcanol Geoth Res, 374, 160-180. doi: 10.1016/j.jvolgeores.2019.02.018.

125. Xu, S., Poppe, A. R., Halekas, J. S., et al., (2019), Mapping the lunar wake potential structure with ARTEMIS data, Journal of Geophysical Research: Space Physics, 124, 3360–3377. doi: 10.1029/2019JA026536.

126. Yang, Y., S. Li, R. E. Milliken, H. Zhang, K. M. Robertson, and T. Hiroi (2019), Phase functions of typical lunar surface minerals derived for the Hapke model and implications for visible to near-infrared spectral unmixing, J. Geophys. Res., 124. Doi: 10.1029/2018JE005713.

127. Zhu, C., Góbi, S., Abplanalp, M.J., Frigge, R., Gillis-Davis, J.J., Dominguez, G., Miljković, K., Kaiser, R.I., 2019. Regenerative water sources on surfaces of airless bodies. Nature Astronomy. doi: 10.1038/s41550-41019-40900-41552.

128. Zhu, C., Crandall, P. B., Gillis-Davis, J. J., Ishii, H. A., Bradley, J. P., Corley, L. M., & Kaiser, R. I. (2019). Untangling the formation and liberation of water in the lunar regolith. Proceedings of the National Academy of Sciences, 116(23), 11165-11170. doi: 10.1073/pnas.1819600116.

129. Zhu, M.-H., Wünnemann, K., Potter, R. W. K., Kleine, T., & Morbidelli, A. (2019). Are the Moon's nearside-farside asymmetries the result of a giant impact? Journal of Geophysical Research: Planets, 124. doi: 10.1029/2018JE005826.